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16. ABSTRACT The six-volume report: describes the theory of a three-dimensional (3-D) mathematical thermal discharge model and a related one-dimensional (1-D) model, includes model verification at two sites, and provides a separate user's manual for each model. The 3-D model has two forms: free surface and rigid lid. The former, verified at Anclote Anchorage (FL), allows a free air/water interface and is suited for significant surface wave heights compared to mean water depth; e.g., estuaries and coastal regions. The latter, verified at Lake Keowee (SC), is suited for small surface wave heights compared to depth (e.g., natural or man-made inland lakes) because surface elevation has been removed as a parameter. These models allow computation of time-dependent velocity and temperature fields for given initial conditions and time-varying boundary conditions. The free-surface model also provides surface height variations with time. The 1-D model is considerably more economical to run but does not provide the detailed prediction of thermal plume behavior of the 3-D models. The 1-D model assumes horizontal homogeneity, but includes area-change and several surface-mechanism effects.

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VERIFICATION AND TRANSFER OF THERMAL POLLUTION MODEL

Volume III: VERIFICATION OF THREE-DIMENSIONAL RIGID-LID MODEL

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PREFACE

The Thermal Pollution Group at the University of Miami has been developing three-dimensional mathematical models for predicting the hydrothermal behaviors of bodies of water subjected to a heated effluent. Generally speaking, these models can be classified in two categories, namely, the free surface models which take into account the variation in water surface elevations and rigid-lid models which treat the water surface as flat.

To enable the prospective user to use these models as accurate predictive tools, particularly to assess the environmental impact in the case of cooling lakes, they have to be calibrated and verified at a number of sites. The present volume describes the application of the rigid-lid model developed by this group to a rather complicated site, namely, Lake Keowee in South Carolina. Lake Keowee is rather unique since it is used by a Nuclear Power Plant as a cooling lake as well as two other hydroelectric stations which use it as lower and upper ponds.

This is the final verification of these models concluding a series of such verifications made possible by funding and technical assistance provided by the National Aeronautics and Space Administration (NASA) and the Environmental Protection Agency (EPA).

This model will eventually be made available to all prospective users by NASA and EPA. The present volume together with the "Three Dimensional Rigid-Lid Model User's Manual" is intended for assisting such future users.

ABSTRACT

The Rigid Lid was developed by the University of Miami, Thermal Pollution Group, to predict three-dimensional temperature and velocity distributions in lakes. This model was verified at various sites (Lake Belews, Biscayne Bay, etc.) and the verification at Lake Keowee was the last of these series of verification runs.

The verification at Lake Keowee included the following phases of work.

1. Selecting the domain of interest, grid systems and comparing the preliminary results with archival data.

2. Obtaining actual ground truth and infrared scanner data both for summer and winter.

3. Using the model to predict the measured data for the above periods and comparing the predicted results with the actual data.

The model results have compared well with measured data. Thus, the model can be used as an effective predictive tool for future sites.

CONTENTS

Preface ii
Abstract iii
Figures v
Tables viii
Symbols ix
Acknowledgments x

1. Introduction 1
   - Background 1
   - Objectives of present work 1
   - Description of Lake Keowee site 2
2. Conclusions 3
3. Recommendations 4
4. Mathematical Formulation and Model Description 5
   - Choice of model 5
   - Description of model 5
   - Governing equations 6
   - Initial and boundary conditions 9
   - Spatial difference schemes 11
   - Stability 12
   - Marker matrices 12
5. Application to Lake Keowee 14
   - Introduction 14
   - Choice of domain and grid system 14
   - Summary of data 15
   - Calculation of input 18
6. Results and Discussions 23

References 29

FIGURES

Number		Page
1	Lake Keowee	30
2	Grid system for the rigid-lid model	31
3	MAR markers matrix (main grid points)	32
4	MRH marker matrix (half grid points)	33
5	Map of area of interest	34
6	Measured isotherms (archival 9/10/75)	35
7	August ground truth data (measuring stations)	36
8	Flight plans for IR data (August and February missions)	37
9	Keowee hydro discharge data (August 24, 1978)	38
10	Keowee hydro discharge data (August 25, 1978)	39
11	Jocassee-pumped storage station discharge data (August 24, 1978)	40
12	Jocassee-pumped storage station discharge data (August 25, 1978)	41
13	Keowee February 1979 showing stations	42
14	Jocassee-pumped storage station discharge data (February 27, 1979)	43
15	Jocassee-pumped storage station discharge data (February 28, 1979)	44
16	Keowee hydro discharge (February 27, 1979)	45
17	Keowee hydro discharge (February 28, 1979)	46
18	Velocities at K = 1 after 8.64 hrs. (L001)	47

FIGURES

Number		Page
19	Velocities at I = 11 after 21.6 hrs. (L001)	48
20	Isotherms measured and predicted after 8.64 hrs. (L001) .	49
21	Velocities at K = 1 after 8.64 hrs. (L002)	50
22	Velocities at I = 11 after 8.64 hrs. (L002)	51
23	Isotherms measured and predicted after 8.64 hrs. (L002) .	52
24	Velocities at K = 1 after 8.00 hrs. (L003)	53
25	Velocities at J = 7 after 4.32 hrs. (L003)	54
26	Isotherms measured and predicted after 8.64 hrs. (L003) .	55
27	Isotherms measured and predicted (L004)	56
28	Velocities at K = 1 after 4.32 hrs. (L005)	57
29	Velocities at J = 7 after 32.4 hrs. (L005)	58
30	Isotherms measured and predicted after 32.40 hrs. (L005)	59
31	Vertical temperature profiles (L005)	60
32	Comparison of surface velocities (I = 11, J = 7, K = 1) ..	61
33	Comparison of surface velocities (I = 11, J = 2, K = 1) ..	62
34	IR Data corresponding to 1002 hrs., August 24, 1978 ...	63
35	Surface isotherms 1002 hrs., August 24, 1978 (30.5, 30.0, 29.5°C)	64
36	Surface isotherms 1002 hrs., August 24, 1978 (29.5, 29.3, 29.1°C)	65
37	IR data corresponding to 0903-0953 hrs., August 25, 1978.	66
38	Surface isotherms 33.23 hrs., August 25, 1978 (30.0, 29.5°C)	67
39	Surface isotherms 33.2 hrs., August 25, 1978 (29.90, 29.70, 29.60°C)	68

FIGURES

Number		Page
40	Velocities at K = 1, 10.07 hrs., August 25, 1978.....	69
41	Velocities at K = 1, 34.24 hrs., August 25, 1978	70
42	IR data corresponding to 1648-1651 hrs., February 27, 1979	71
43	Surface isotherms 17.12 hrs., February 27, 1979 (13.0, 12.75, 12.5, 12.0, 11.5, 11.0°C).....	72
44	Surface isotherms 17.12 hrs., February 27, 1979 (13.75, 13.0, 12.5, 12.0°C)	73
45	IR data corresponding to 0948-0957 hrs., February 28, 1979	74
46	Surface isotherms 34.2 hrs., February 28, 1979 (13.0, 12.5°C)	75
47	Velocities at K = 1, 17.12 hrs., February 27, 1979	76
48	Velocities at K = 1, 34.24 hrs., February 28, 1979	77

TABLES

Number		Page
1	Monthly Gross Thermal Capacity Factors of Oconee Nuclear Station	78
2	Operating Conditions of Oconee Nuclear Power Plant (September 10, 1975)	79
3	Input Data for 3-D Model (Lake Keowee)	80
4	Volume and Area Data for Lake Keowee	81
5	Inflows and Outflows to Lake Keowee, August 24, 1978 ..	82
6	Inflows and Outflows to Lake Koewee, August 25, 1978 ..	83
7	Meteorological Data for Lake Keowee, August 24, 1978 ...	84
8	Meteorological Data for Lake Keowee, August 25, 1978 ...	85
9	Inflows and Outflows to Lake Keowee, February 27, 1979 .	86
10	Inflows and Outflows to Lake Keowee, February 28, 1979 .	87
11	Meteorological Data for Lake Keowee, February 27, 1979 ..	88
12	Meteorological Data for Lake Keowee, February 28, 1979 ..	89
13	Summary of Runs for Lake Keowee	90
14	Root Mean Square Difference Between IR and Predicted Temperatures	91

SYMBOLS

A_H	Horizontal kinematic eddy viscosity
A_V	Vertical kinematic eddy viscosity
A_{ref}	Reference kinematic eddy viscosity
A_V^*	A_V/A_{ref}
B_H	Horizontal eddy thermal diffusivity
B_V	Vertical eddy thermal diffusivity
B_{ref}	Reference eddy thermal diffusivity
B_V^*	B_V/B_{ref}
C_p	Specific heat at constant pressure
Eu	Euler number
f	Coriolis parameter
g	Acceleration due to gravity
h	Depth relative to the mean water level
H	Reference depth
I	Grid index in x-direction or α direction
J	Grid index in y-direction or β direction
K	Grid index in z-direction or γ direction
K_S	Surface heat transfer coefficient
L	Horizontal length scale
P	Pressure
P_S	Surface pressure
Pr	Turbulent Prandtl number, A_{ref}/B_{ref}
Pe	Peclet number
Q	Heat sources or sinks
Re	Reynolds number (turbulent)
Ri	Richardson number
T	Temperature
T_{ref}	Reference temperature
T_s^e	Equilibrium temperature
T_s	Surface temperature
t	Time
t_{ref}	Reference time
u	Velocity in x-direction
v	Velocity in y-direction
w	Velocity in z-direction
x	Horizontal coordinate
y	Horizontal coordinate
z	Vertical coordinate

Greek Letters

α	Horizontal coordinate in stretched system, = x
β	Horizontal coordinate in stretched system, = y
γ	Vertical coordinate in stretched system
σ	Constant in vertical diffusivity equation, or vertical coordinate in stretched system, = Z/H
Ω	Transformed vertical velocity
ρ	Density
τ_{xz}	Surface shear stress in x-direction
τ_{yz}	Surface shear stress in y-direction

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SECTION 1

INTRODUCTION

BACKGROUND

Understanding the environmental impact of hot water discharge from the condenser of a steam power plant is of considerable importance in helping to preserve aquatic life and also the overall efficiency of the power plant. In recent years, with the improvement of computing facilities, a number of different types of mathematical models have been developed to predict such effects. These models, if properly calibrated, are extremely useful in determining the complete environmental impact arising due to normal as well as abnormal operating conditions, which may be difficult to realise experimentally. This is particularly important with respect to estimating these adverse effects during the planning stages, thus, helping to minimize them in the final construction.

The mathematical models solve the basic fluid flow and energy transfer equations subject to certain simplifications and assumptions. These may be used to determine the long term heat budget for the cooling lake as well as determine the detailed velocity and temperature distributions within it. The accuracy of predictions using these models is extremely important and the only way to verify this is to apply these models to certain known sites and compare the predicted values with actual measured quantities. Measurements may be obtained by measuring the water velocities and temperatures with anemometers and thermometers as well as by infrared remote sensing photography. Each of these techniques has its own advantages and disadvantages. To get a proper representative data base, all of these have to be used simultaneously. Other factors which affect the water conditions are the meteorological conditions, viz. wind speed, solar radiation, air temperature and humidity.

OBJECTIVES OF PRESENT WORK

For the past several years the thermal pollution group at the University of Miami has developed a number of mathematical models for both long and short term simulation. The model considered here is a three-dimensional rigid-lid model designed for short time prediction of detailed three-dimensional velocity and temperature profiles in the region of the thermal plume. This model has been applied in the past years to several sites, namely, Lake Belews (Lee, Sengupta, Mathavan, 1977). The predictions of the model at the above sites compared reasonably well with measured data. The results of these runs have been published by the University of Miami in

earlier volumes in cooperation with NASA.

The success of this model at the above sites led to the belief that this model could be used in future predictions. It was mainly for this reason that a site was chosen which was quite complex in nature and which would bring out the prediction capabilities and limitations of the model. This would also be of great help to future users of the model in order to obtain a proper interpretation of the results when used as a predictive tool.

Lake Keowee in South Carolina provides such a site; hence it was chosen for the final verification of the model. A description of the site is given in the following section.

DESCRIPTION OF LAKE KEOWEE SITE

Lake Keowee is located on the north of the state of South Carolina about 40 km west of Greenville. It was made from 1968 through 1971 by damming the Little River and Keowee River. At present, it constitutes Duke Power Company's Keowee Toxaway Complex.

The lake has two arms connected by a canal (maximum depth 30.5 m). There are three power plants on it, namely, the Oconee Nuclear Station, Keowee Hydro Station and Jocassee-Pumped Storage Station. The Oconee Nuclear Station is a three-unit steam-electric station with an installed capacity of generating 2580 MW. The Oconee Nuclear Station draws in condenser cooling water from the lower arm of Lake Keowee and discharges the heated effluent to the upper arm of the lake. The intake structure for the condenser cooling water allows water from 20 to 27 m depth (full pond) to pass through. The discharge structure has openings from 9 to 12 meters deep through which the CCW returns directly to the lower arm of Lake Keowee.

Lake Jocassee is located north of Lake Keowee and is used as a reservoir for Jocassee-pumped storage station. The upper arm of Lake Keowee also serves as the lower pond for Jocassee-pumped storage station. The Jocassee Station has reversible turbines with a maximum generating flow (into Lake Keowee) of about 820 m^3/sec and a maximum pumping flow of about 775 m^3/sec; the net flow into Lake Keowee from Lake Jocassee is about 15.5 m^3/sec.

Lake Keowee has a full pond elevation of 243.8 m above mean sea level. At full pond it has a volume of approximately 1.18×10^9 m^3, an area of 74 km^2, a mean depth of 15.8 m and a shoreline of about 480 km. The outflow from Lake Keowee is through Keowee hydro station. The flow through Keowee hydro station varies from 1.4 m^3/sec (leakage) to 560 m^3/sec (during peak load operation). The maximum draw down of the lake is 7.6 m.

A map of Lake Keowee is shown in Figure 1. The above data was obtained from Duke Power Company 1976.

SECTION 2

CONCLUSIONS

The main objective of this work was to prepare a mathematical model package to assess environmental impact due to a heated effluent. Hence, the final test for the model was at Lake Keowee. The reasonably good agreement of the predictions with data was shown in the last section. The shape of the plume, as predicted by the model resembles closely but does not correspond exactly to the plumes obtained from the IR scanner photographs. An important comparison in this case is the area covered by each isotherm which gives an indication of the spread of the heated effluent. This area is approximately the same in the measured and predicted cases for both summer and winter runs. Another way the accuracy of the model was determined was by the root mean square deviations of the temperature between predicted and measured values over the entire domain. These deviations are shown in Table 14.

The accuracy of the IR scanner isotherms is about 0.5°C (from the sensitivity of the process). The accuracy of the position of the isotherms is within ± 0.5 x (grid space) in this case resulting from the lateral distortion in the Digicolor map and the process of transfering this on to the computational grid for the purpose of comparison.

Based on the above results, it may be concluded that the predictions made by the model are reasonable beyond doubt when applied to cooling lakes or a similar site. Hence, the model may be used as a predictive tool for obtaining three-dimensional temperature and velocity profiles in the vicinity of a thermal effluent discharge, and the results may be used in evaluating the performance of existing or future thermal power plants.

SECTION 3

RECOMMENDATIONS

Various numerical models have been developed to study the effects of heated discharge and meteorological conditions on bodies of water. Most of these models are one or two dimensional. These models have a high computational speed but only give horizontally or vertically averaged values of temperatures.

Three-dimensional models, however, have a much finer resolution but they consume larger computer time. The three-dimensional rigid-lid model can be used to obtain detailed temperature and velocity distributions in a domain where surface gravity waves are small compared to the depth of the domain. This model, as compared to free-surface models, runs faster since surface gravity waves are eliminated by this rigid-lid assumption.

A proper method of using this model would be to run a one-dimensional model initially to obtain a rough picture of the temperatures and then using this model to obtain a better resolution, the 1-D results being used as ambient conditions.

The following improvements have been suggested for the model.

1. Since all natural flows are turbulent, proper turbulent closures are needed to make the model meaningful. At present, the simplest possible closures, namely constant eddy viscosities and eddy diffusivities, have been used. However, better results may be obtained by using a higher order closure.

2. At present, the model uses uniform horizontal grids and stretched vertical grids. Nonuniform horizontal grids could be introduced for better resolution near the boundaries.

3. The program has been written to be run as a batch-job on the computer. It could be made interactive so as to enable the user to run it on a terminal. However, this would require some modifications in order to reduce the storage space.

SECTION 4

MATHEMATICAL FORMULATION AND MODEL DESCRIPTION

CHOICE OF MODEL

Two three-dimensional models have been developed by the thermal pollution group at the University of Miami. The first one is a free-surface model, which takes into account the variation in surface heights of a basin. The second one is the rigid-lid model which assumes the vertical velocities on the water surface as zero. These models have been described in previous publications of this group. The choice of a particular model for simulating flows depends on the nature of the site.

Lake Keowee is a relatively small, closed basin with maximum depth of 30 m. The small horizontal numerical grid dimensions demand extremely small integration time steps to satisfy the Courant-Lewy-Fredrichs conditions inherent in free-surface formulations. Since the surface waves are small compared to the depth, i.e. $h/H \ll 1$, a rigid-lid formulation is suitable. This rigid-lid model allows acceptable accuracy with acceptable time step size since the C.L.F. criterion is eliminated. This makes the rigid-lid model a rather obvious choice.

The rigid-lid model has been applied previously to Biscayne Bay and Lake Belews sites with reasonable accuracy, as mentioned in the previous section. This led to the belief that it would be ideally suited for the Keowee site.

DESCRIPTION OF THE MODEL

(Portions of the following section have been published earlier by this group.)

The rigid-lid model has the following capabilities:

1. Predict the wind-driven circulation.
2. Predict the circulation caused by inflows and outflows to the domain.
3. Predict the thermal effects in the domain.
4. Combine the aforementioned processes.

The model solves equations for fluid flow (momentum and continuity)

and heat transfer together with the equation of state in a three-dimensional domain. Since most geostrophic flows are turbulent, the resulting Reynolds stress terms in the governing equations are replaced by eddy transport coefficients. The fluid is considered to be an incompressible Boussinesq fluid and the hydrostatic assumption has been made.

The rigid-lid assumption imposes a zero vertical velocity condition on the surface without affecting the horizontal velocities. This causes the surface pressure to be different from atmospheric which under special conditions may be translated into surface gravity wave heights if no lid is present. This assumption distorts transient time scales but does not affect circulation patterns as has been demonstrated by Berdahl (1970), Crowley (1969, 1970), Hag and Lick (1973) and Young, Liggett and Gallagher (1976). Since surface gravity waves no longer have to be reproduced, computer time is saved considerably and this assumption is quite adequate for cooling lake studies where surface waves are not large and do not change rapidly.

To convert regions having irregular bottom topography to constant depth regions for computation stability a vertical stretching, suggested by Freeman et al. (1972), has been used.

GOVERNING EQUATIONS

The vertical stretching used in the rigid-lid model, originally adopted by Sengupta and Lick (1974), is of the form

$$\gamma = \frac{\tilde{z}}{\tilde{h}(x,y)}$$

This enables the same number of grid points to be used all over the domain without using variable grid sizes. The resulting nondimensional governing equations in the new (α,β,γ) coordinate system instead of $(\tilde{x},\tilde{y},\tilde{z})$ are

Continuity Equation:

$$\frac{\partial(hu)}{\partial\alpha} + \frac{\partial(hv)}{\partial\beta} + h\frac{\partial\Omega}{\partial\gamma} = 0$$

Momentum Equation:

$$\frac{\partial(hu)}{\partial t} + \frac{\partial(huu)}{\partial\alpha} + \frac{\partial(huv)}{\partial\beta} + h\frac{\partial(\Omega u)}{\partial\gamma} - \frac{h}{R_B}v$$

$$= -h\frac{\partial P_s}{\partial\alpha} - hB_x + \frac{1}{R_e}\left(h\frac{\partial u}{\partial\alpha}\right) + \frac{1}{R_e}\frac{\partial}{\partial\beta}\left(h\frac{\partial u}{\partial\beta}\right)$$

$$+ \frac{1}{\varepsilon^2 R_e} \frac{1}{h} \frac{\partial}{\partial \gamma} \left(A_V^* \frac{\partial u}{\partial \gamma}\right) \quad \text{(For the 'α' direction).}$$

Hydrostatic Equation:

$$\frac{\partial P}{\partial \gamma} = E_u (1 + \rho) h$$

Energy Equation:

$$\frac{\partial (hT)}{\partial t} + \frac{\partial (huT)}{\partial \alpha} + \frac{\partial (hvT)}{\partial \beta} + h \frac{\partial (\Omega T)}{\partial \gamma}$$

$$= \frac{1}{P_e} \frac{\partial}{\partial \alpha} h \left(\frac{\partial T}{\partial \alpha}\right) + \frac{1}{P_e} \frac{\partial}{\partial \beta} \left(h \frac{\partial T}{\partial \beta}\right)$$

$$+ \frac{1}{P_e \varepsilon^2} \frac{1}{h} \frac{\partial}{\partial \gamma} \left(B_v^* \frac{\partial T}{\partial \gamma}\right)$$

Equation of State:

$$\tilde{\rho} = 1.029431 - 0.000020\, \tilde{T} - 0.0000048\, \tilde{T}^2$$

where $\tilde{\rho}$ is in gm/cc and T is in °C

and $$\tilde{w} = \left(u \frac{\partial \tilde{h}}{\partial \tilde{x}} + \tilde{v} \frac{\partial \tilde{h}}{\partial \tilde{y}}\right) + \tilde{h} \tilde{\Omega}$$

where $$\tilde{\Omega} = \frac{\partial \gamma}{\partial \tilde{t}}$$

and $$\tilde{w}(\tilde{Z}=0) = 0 \quad \text{(rigid lid)}$$

where $$u = \tilde{u}/U_{ref}, \; v = \tilde{v}/U_{ref}, \; w = \tilde{w}/\varepsilon U_{ref}$$

$$t = \tilde{t}/t_{ref}, \; x = \tilde{x}/L, \; y = \tilde{y}/L, \; Z = Z/H$$

$$\varepsilon = H/L, \; P = \tilde{P}/\rho_{ref} U^2_{ref}, \; T = \frac{T - \tilde{T}_{ref}}{T_{ref}}$$

$$\rho = \frac{\bar{\rho}_{ref}}{\rho_{ref}}, \; A_H^* = A_h/A_{ref}, \; A_v^* = A_v/A_{v_{ref}}$$

$$B_H^* = B_H/B_{ref}, \; B_v^* = B_v/B_{ref}$$

$$t_{ref} = L/U_{ref}$$

Quantities with subscript 'ref' are reference quantities; H and L are vertical and horizontal length scales. The variables with wavy lines on top are dimensional quantities.

$$\text{If } A_H = A_{ref} \text{ and } B_H = B_{ref} \text{ then } A_H^* = 1 = B_H^*$$

$$R_e = \frac{U_{ref} L}{A_{ref}},\ R_B = \frac{U_{ref}}{fL},\ P_r = \frac{A_{ref}}{B_{ref}}$$

$$P_e = R_e,\ P_r = \frac{U_{ref} L}{B_{ref}},\ E_u = \frac{gH}{U_{ref^2}}$$

If Prandtl number is equal to 1, then $A_{ref} = B_{ref}$.

A_H and A_v are the eddy viscosities in horizontal and vertical directions.

B_H and B_v are the eddy diffusivities in horizontal and vertical directions.

To obtain a predictive equation for pressure, the horizontal momentum equations are integrated from Z=0 to Z=h, where h is the nondimensional depth $\hat{h}/H$. The integrated equations are then differentiated with respect to α and β summed.

The Poisson equation for surface pressure becomes:

$$\frac{\partial^2 P_s}{\partial \alpha^2} + \frac{\partial^2 P_s}{\partial \beta^2} = \frac{1}{h}\frac{\partial}{\partial \alpha}(-A_{x_1} + A_{x_2} + C_x - x_p)$$

$$+ \frac{1}{h}\frac{\partial}{\partial \beta}(-A_{y_1} - A_{y_2} + C_y - Y_p)$$

$$- \frac{1}{h}\left\{\frac{\partial h}{\partial \alpha}\frac{\partial P_s}{\partial \alpha} + \frac{\partial h}{\partial \beta}\frac{\partial P_s}{\partial \beta}\right\} - \frac{\partial (\Omega)}{\partial t}(Z=0)$$

The last term is the Hirt and Harlow (1964) correction term which accounts for nonzero vertical velocities at the rigid lid. The variables (B_x, B_y, and A_{x_1}, A_{x_2} etc.) are given below:

$$A_{x_1} = \int_0^1 \left\{\frac{\partial}{\partial \alpha}(huu) + \frac{\partial}{\partial \beta}(huv) + h\frac{\partial}{\partial \gamma}(\Omega u)\right\} d\gamma$$

$$A_{x_2} = \frac{h}{R_B} \int_0^1 v d\gamma$$

$$C_x = \frac{1}{R_e} \int_0^1 \{\frac{\partial}{\partial \alpha}(h\frac{\partial u}{\partial \alpha}) + \frac{\partial}{\partial \beta}(h\frac{\partial u}{\partial \beta}) + \frac{1}{\varepsilon^2}\frac{1}{h}\frac{\partial}{\partial \gamma}(A_v^* \frac{\partial u}{\partial \gamma})\} d\gamma$$

$$X_p = E_u \int_0^1 h\{\frac{\partial h}{\partial x}\int_0^\gamma \rho d\gamma + h\frac{\partial}{\partial \alpha}\int_0^\gamma \rho d\gamma - \gamma\frac{\partial h}{\partial \alpha}\rho\} d\gamma$$

$$A_{y_1} = \int_0^1 \{\frac{\partial}{\partial \alpha}(huv) + \frac{\partial}{\partial \alpha}(huv + h\frac{\partial(\Omega v)}{\partial \gamma}\} d\gamma$$

$$A_{y_2} = \frac{h}{R_B} \int_0^1 u d\gamma$$

$$C_y = \frac{1}{R_e} \int_0^1 \{\frac{\partial}{\partial \alpha}(h\frac{\partial u}{\partial \alpha}) + \frac{\partial}{\partial \beta}(h\frac{\partial u}{\partial \beta}) + \frac{1}{\varepsilon^2}\frac{1}{h}\frac{\partial}{\partial \gamma}(A_v^* \frac{\partial u}{\partial \gamma})\} d\gamma$$

$$Y_p = E_u \int_0^1 h\{\frac{\partial h}{\partial \beta}\int_0^\gamma \rho d\gamma + h\frac{\partial}{\partial \beta}\int_0^\gamma \rho d\gamma - \gamma\frac{\partial h}{\partial \beta}\rho\} d\gamma$$

$$B_x = E_u \frac{\partial h}{\partial \alpha}\int_0^\gamma \rho d\gamma + E_u h\frac{\partial}{\partial \beta}\int^\gamma \rho d\gamma - E_u \gamma\frac{\partial h}{\partial \beta}\rho$$

The set of equations (24-30) together with appropriate boundary conditions constitute the mathematical model. The model has been described in earlier publications by this group (Lee and Sengupta, 1976).

INITIAL AND BOUNDARY CONDITIONS

The nature of the equations requires initial and boundary conditions to be specified. As the initial condition, the velocities, temperatures and densities are specified throughout the domain. Boundary conditions are specified at the air-water interface, geographical boundaries of the domain, the bottom of the basin and the efflux points. At the air-water interface a wind stress and a heat transfer coefficient are specified. The conditions on the lateral walls are no-slip and no-normal velocity for the momentum equations. These walls are assumed to be adiabatic. At the floor of the basin, the conditions of no-slip and no-normal velocities are applicable. The energy equation has a heat flux boundary condition.

At points of efflux open-boundary conditions are specified. If the flows are known at the points of efflux, the flow velocities are specified. Usually, the temperature is known only at the point where the heated discharge (from the power plant) enters the domain. At points where the temperatures are not explicitly known, open-boundary condition (i.e. zero gradient condition) is specified. The same holds true if the velocities are not explicitly known (e.g. the connecting canal between the

two arms of Lake Koewee).

Hence, the boundary conditions are:

At the surface

$$\gamma = 0$$

$$\Omega = 0 \text{ (Rigid Lid)}$$

$$\frac{\partial u}{\partial \gamma} = \left(\frac{hH}{U_{ref} A_v}\right) \tau_{zx}$$

$$\frac{\partial T}{\partial \gamma} = \left(\frac{hHK_s}{B_z}\right) (T_E - T_s)$$

$$\frac{\partial v}{\partial \gamma} = \left(\frac{hH}{U_{ref}} A_v\right) \tau_{zy}$$

where τ_{zx} and τ_{zy} are wind stresses in the x and y-directions respectively.

T_E is the equilibrium temperature.

T_s is the water surface temperature.

K_s is the surface heat transfer coefficient.

τ_{zx} and τ_{zy} are calculated from the wind velocity using Wilson curve (B. W. Wilson, 1960).

K_s and T_e are calculated as follows:

$$K_s = 4.5 + 0.05\, T_s + BF(w) + 0.47(w) \; (wm^{-2}{}^{\circ}C^{-1})$$

where T_s is in °C.

$F(w) = 9.2 + 0.46\, W^2 \; (wm^{-2}mmHg^{-1})$.

$B = 0.35 + 0.015\, T_m + 0.0012\, T_m{}^2 \; (mmHg/{}^{\circ}C)$.

$T_m = (T_s + T_d)/2 \; (^{\circ}C)$.

T_d = Dewpoint temperature (°C).

$T_E = T_d + H_s/K_s$.

H_s = Surface solar radiation (w/m^2).

At the bottom of the basin

$$\gamma = 1$$

$$\Omega = 0$$

$$u = 0$$

$$v = 0$$

$$\frac{\partial T}{\partial \gamma} = 0$$

On lateral walls

$$u = 0$$

$$v = 0$$

$$\Omega = 0$$

$$\frac{\partial T}{\partial x} = \frac{\partial T}{\partial \alpha} - \frac{\gamma}{h}\frac{\partial h}{\partial \alpha}\frac{\partial T}{\partial \gamma} = 0$$

$$\frac{\partial T}{\partial y} = \frac{\partial T}{\partial \beta} - \frac{\gamma}{h}\frac{\partial h}{\partial \beta}\frac{\partial T}{\partial \gamma} = 0$$

SPATIAL DIFFERENCE SCHEMES

The numerical solution of the momentum and energy equations are explicit. The values of velocities and temperatures at a future time are determined completely using the values at the present and previous time steps. Finite difference forward time and central space difference schemes are used. Diffusion terms are written using a Dufort-Frankel finite difference scheme to relax the diffusive stability criterion. The convective stability criterion, however, is not affected.

A horizontal staggering is used in the computational grids. Horizontal velocities and temperatures are calculated at the main-grid points while vertical velocities and pressures are calculated at half-grid points

The predictive Poisson equations for calculating rigid-lid pressures is finite differenced using a five-point scheme. This is solved by successive over relaxation (Liebmann Method). Terms on the right hand side of the pressure equation are obtained by integrating terms in the horizontal momentum equations over the depth using the trapezoidal rule.

At the boundaries, single-sided schemes are used since the boundary points do not have two adjacent points. A curve is fitted through the

two most adjacent points towards the interior of the domain. The values of the variables, where they are not defined, are obtained by averaging the values at four points around the point where the values are defined.

STABILITY

It is not possible to make a strict stability analysis of the system of equations under consideration. It is customary, however, to take advantage of the stability analysis for the one-dimensional Burger's equation since this contains an unsteady term, a convective term and a diffusion term.

In the present case these criteria can be written as follows for the choice of the time step $\Delta\tilde{t}$

Convective

$$\Delta\tilde{t} < \frac{\Delta\tilde{x}}{U}$$

where U is the maximum horizontal velocity in the domain.

Diffussive

$$\Delta\tilde{t} < \frac{(\Delta\tilde{x})^2}{2A_H}$$

MARKER MATRICES

Since natural bodies of water have irregular boundaries, the physical boundaries have to be approximated in a rectangular coordinate system using marker matrices (Fortran variable MAR for the full grids and MRH for the half grids). The convention used is as follows:

MAR = 0, point outside the region of interest (i.e., on dry land)

In approximating such a boundary using a rectangular grid system only a portion of the resulting grid falls within the water. To prevent computations to be carried out on dry land markers have to be used to distinguish between points lying within and outside the region of interests. Such markers have to be used both for the main and half-grid points. Fortran symbols used are MAR for the main grid and MRH for the half-grid system. The convention used is as follows:

MAR = 0, point outside the region of interest (i.e., on dry land).

MAR = 1, point on far y-boundary.

MAR = 2, point on near y-boundary.

MAR = 3, point on near x-boundary.

MAR = 4, point on far x-boundary.

MAR = 5, outside corner, on near x-boundary and far y-boundary.

MAR = 6, inside corner on far x-boundary and far y-boundary.

MAR = 7, outside corner on near x-boundary and near y-boundary.

MAR = 8, inside corner on near x-boundary and near y-boundary.

MAR = 9, outside corner on far x-boundary and near y-boundary.

MAR = 10, outside corner on far x-boundary and far y-boundary.

MAR = 11, interior points (within region of interest).

Similarly for the half-grid points.

MRH = 1, corner on far x-boundary and far y-boundary.

MRH = 2, points on near y-boundary.

MRH = 3, points on near x-boundary.

MRH = 4, corner at near x- and near y-boundaries.

MRH = 6, far corner on x-axis.

MRH = 7, corner at far x- and y-boundaries.

MRH = 9, interior grid points.

SECTION 5

APPLICATION TO LAKE KEOWEE

INTRODUCTION

The three-dimensional rigid-lid model described in Chapter II has been applied to Lake Keowee, South Carolina, to predict the wind-driven circulation, circulation caused by inflows and outflows, and the thermal dynamics of a region of this lake. This region includes the buoyant plume, the Keowee hydro dam, the connecting canal and an open-boundary where the effects of inflow and outflow to Jocassee-pumped storage station are felt.

Lake Keowee is a warm monomictic lake having one circulation period during the year, beginning in fall, and is thermally stratified during the summer. During the circulation period, the water mass is vertically mixed. This type of lake can also be termed holomictic (Hutchinson, 1957). Lake Keowee could also be classified as a subtropical lake as it exhibits thermal stratification, a period of total circulation preceded by the fall overturn, and surface temperatures above 4°C. The highest surface temperatures typically occurred in July and August and ranged from approximately 27 to 29°C. During the periods from November through February the lake was isothermal or nearly so. It can be concluded from the above that a series of meteorological events primarily govern Lake Keowee's thermal characteristic. However, as will be shown below, the near field region which makes up the region of interest in this present study, is very strongly affected by the buoyant plume, inflow and outflow and the Jocassee-pumped storage station.

CHOICE OF DOMAIN AND GRID SYSTEM

The region of interest has already been mentioned in the last section. Here, an attempt will be made to justify this choice and then a description of the grid system will be given.

The study and prediction of the thermal impact on the hydro-dynamics of Lake Keowee has been done in two main sections:

1. Using a 1-D continuous temperature profile prediction model over the period 1971-1979, the area of interest includes the two main arms of Lake Keowee and the connecting canal. The application of this model has been published by the thermal pollution group of the University of Miami (Sengupta et al 1980).

2. Using the 3-D rigid-lid model, which is described in this report.

The division has been necessary since the 1-D model predicts temperature profiles continuously over a period of time (several years if required); it can be used to predict the initial conditions required to run the 3-D model. The 3-D model, on the other hand, has better resolution and is therefore used for predicting the near-field thermal impact on the lake. This near-field area of interest is shown in Figure 5. In selecting this area some preliminary runs were made. These are described later.

The region of interest is divided into a square grid as shown in Figure 5. The I and J axes (corresponding to u and v-velocity axes) are numbered as shown in the above figure. For the top 'open boundary', 'J' increases from 7 to 20. The left side boundary shown 'I' increasing from 1 to 17; the right side boundary shows 'I' increasing from 1 to 16, and finally, the bottom boundary shows 'J' increasing from 1 to 18. The orientation of these boundaries with the north-south direction is also shown in this figure. The squares are (152.4 x 152.4) square meters. Arrows indicate directions of flow into or out of domain.

SUMMARY OF DATA

For the purposes of calibrating and verifying the model, an archival data base was established and two remote sensing and field data collection missions (summer and winter) were undertaken.

Archival Data Base

The archival data base are summarized in Figure 6 and Tables 1 through 4. These figures were taken from Duke Power Company (1976). Figure 6 shows the measured surface isotherms for September 10, 1975. This figure constitutes the data base on which the comparisons for the preliminary and archival runs are based. The runs are described below. Table 1 shows the monthly gross thermal capacity factors for Oconee Nuclear Station (1973-1977). Table 2 is a summary of Oconee Nuclear Power Plant for September 10, 1975. Table 3 shows the input data used for the preliminary and archival runs. The data include the flow-rate, inlet temperature, discharge temperature and velocity, ambient temperature, depth at discharge, discharge width, air temperature, wind speeds and the vertical and horizontal eddy diffusivities. Table 4 is a summary of the volume and area data for Lake Keowee.

August 1978 Data

To obtain an understanding of seasonal behavior of Lake Keowee, data was gathered both in summer and winter. This data was used to verify temperatures predicted by the model. Two extreme weather conditions were selected with the idea that if the model predictions were accurate for these conditions it would be so for other intermediate con-

ditions (viz., spring or fall).

In spite of the fact that the model was used for predictions in the vicinity of the thermal plume, temperature and velocity readings were taken for the entire lake. This was done in order to ensure completeness of the data and also to check the choice of the domain of interest within the lake.

Summer data missions were carried out during the period of August 24 and 25, 1978. The data collection team consisted of representatives from NASA, EPA, University of Miami and Duke Power Company. Three boats provided by Duke Power Company were used in the collection of ground truth data. The data collection stations are shown in Figure 7. This included measurements of water temperatures at various depths (from the surface to about 30 m) using YSI type thermistors and velocity measurements using an Endeco Type 110 current meter. The thermistors were calibrated before each set of readings using a mercury thermometer. At each measuring station the boat was anchored and the thermistors and velocity meters were lowered by cables. The cables were marked thus indicating the depth below the water surface where readings were taken. The current meter indicated both the magnitude and direction of the horizontal component of the water velocity. The main problem encountered here was that most of the velocities were very small and close to the threshold of the instrument. Hence, drogues were used to determine average surface velocities.

While the ground truth data was being collected, overflights were made by NASA aircraft to obtain synoptic IR scanner data. The aircraft, a twin engined (Beechcraft) (NASA-6), was specially equipped for this purpose. Flights were made at altitudes of 1000, 2000 and 3000 ft. A diagram of the flight plan is shown in Figure 8. The scanner photographs were taken with window settings between 78 and 84°F. To correct the IR scanner photographs with the ground truth data for each set of flights, the water surface temperature was measured with the aircraft overhead for at least one station. This was to correct the scanner readings due to errors caused by water vapor attenuation.

The scanner used was a daedalus series DS-1250 and remote sensing of 8-14 μm radiation is achieved by a Hg: Cd: detector. The detector had a 0.015 inch square sensitive area, which was optimum for the resolution and temperature sensitivity required. This detector was mounted in an end-looking, metal cored dewar which had sufficient liquid nitrogen coolant capacity for approximately six hours of operation before refilling. This system projected through the floor of the airplane, NASA 6, and had a scan angle of 120° centered above the vertical. A horizontally-mounted telescope with its axis along the direction of flight of the airplane was contained within the scanner. A mirror rotating at 3600 RPM and mounted at 45° to the telescope directed heat radiation from the ground into the system. A one-third revolution of the mirror covered a complete step perpendicular to the scanner axis. Optical resolution

obtained by this method was about 1.7 milliradians, so the ground areas detected become a function of flight altitude; the data accuracy is 0.5°C.

The video signal from the infrared detector was amplified and recorded on magnetic tape in the aircraft. A method developed by Daedalus called Digicolor was used to convert this stored information directly into color coded strip imagery. This process limits the number of output colors to light (from white 'hottest' to black 'coldest') for any input condition. The six colors between white and black indicate the six calibrated levels of the set of interest. The scanner's thermal reference sources were present in flight to 66°F and 84°F respectively, and the settings were recorded on the same track with the detector video to insure accurate voltage relationships irrespective of all amplifier gain adjustments.

The color bands in the final Digicolor map indicate zones of constant temperature within the accuracy of resolution of the scanner; hence, the line formed by the junction of two adjacent color bands indicate an isotherm. The actual temperature of the isotherm is obtained by adding a ground truth correction term to the temperature indicated in the map.

Altogether, three IR flights were made during the summer data collection mission. Out of these, two runs were made on August 24. The first run was from 0853 hrs EST. On August 25, a single run was made from 0908 hrs to 0953 hrs EST.

The Digicolor maps were transfered on to enlarged maps of the region of interest so as to obtain a map of surface isotherms which could be compared directly with the values predicted by the model. Out of the three runs made, only two, namely August 24 morning and August 25 morning, were used for comparisons since the resolution of the colors in the remaining Digicolor map was very poor.

The values of Oconee Nuclear Stations flows and temperatures every hour are obtained from continuous water quality monitoring stations of Duke Power Company. Flow through Jocassee-pumped storage station and Keowee Hydro Station as well as meteorological conditions (viz., air temperature, wind speed and direction, humidity and incident solar radiation) were also obtained from continuous monitoring stations. The flows through Jocasse, Keowee and Oconee as well as the discharge temperatures are shown in Tables 5 and 6. The meteorological data (obtained hourly) are shown in Tables 7 and 8. Figures 9 and 10 show the hourly variation of Keowee Hydro Station flowrate on these two days. Figures 11 and 12 show the same for Jocassee-pumped storage station.

February 1979 Data

The winter data mission was carried out during February 27, 28, 1979. The same equipment were used in this mission. Three boats were used to measure water temperatures and velocities up to a depth of 30 m. Two of the boats were equipped with thermistors only and were

used to measure temperatures in both branches of Lake Keowee. The third boat carried the current meter as well as a thermistor. The stations where readings were taken are indicated in Figure 13. Station #13 was used for ground truth correction of the IR scanner data. This point was chosen since it is virtually unaffected by the discharge, and the temperatures here remained fairly constant.

Ground truth measurements were taken from 0950 hrs to 1353 hrs EST and 1600 hrs to 1833 hrs EST on February 27. Due to technical problems with the aircraft (NASA-6) the IR flights were delayed and were only from 1549 hrs to 1711 hrs EST on this date. The flight plan was identical to that used in the August data mission. Black body settings of 38°F and 74°F were used and the flight altitudes were 2000, 3000 and 1000 feet.

On Feburary 28, 1979 ground truth measurements using three boats were taken from 0851 hrs to 1201 hrs EST and 1420 hrs to 1830 hrs EST. IR flights were run from 0850 hrs to 1002 hrs at altitudes of 2000 and 3000 ft. The black body settings used were established by NASA. IR isotherms were constructed for the domain of interest at the University of Miami. These maps were used for verifying the results predicted by the computer.

For obtaining meteorological data and flows through Oconee Nuclear Station, Jocassee-pumped storage station and Keowee Hydro Station, continuous monitoring stations of Duke Power Company, were used. Since the velocities in the lake were found to be extremely small, drogues were also used. The flows through the three power stations are shown in Tables 9 and 10. The data obtained was hourly and the variation of the flows through Jocassee and Keowee are shown in Figures 14 and 15 and Figures 16 and 17 respectively. The meteorological data collected on February 27 and 28 are shown in Tables 11 and 12 respectively.

The ground truth data collected during the summer and winter missions are presented by Duke Power Company (1978 and 1979).

CALCULATION OF INPUT

The 3-D rigid-lid model as described in Section 4 solves the three-dimensional momentum, continuity and energy equations. As shown before, these equations are a set of nonlinear, coupled partial differential equations and require the following for complete solution.

1. Initial values of the velocities and temperatures must be specified at all points within the domain.

2. Boundary conditions for the above variables must be specified at all boundaries.

The choice of the domain of interest as well as the grid system has

been described in earlier sections. At all solid boundaries the velocities and temperature gradients are specified as zero. At the surface the rigid-lid constraint of zero vertical velocities is assumed. The initial conditions assumed for starting the runs are zero velocities and constant temperatures everywhere within the domain. For subsequent runs the results of the previous run is used as the initial condition. Hence, the quantities yet to be specified are:

1. Temperatures and flow velocities at the Oconee Nuclear Station discharge.

2. Temperatures and velocities at the Keowee Hydro Station.

3. The same at the Jocassee boundary and at the canal. (Items 1 and 2).

4. Surface horizontal velocities and temperatures.

The above quantities are termed as inputs to the model and the procedure used for obtaining them are discussed briefly below for the sake of completeness. For further details regarding the actual running of the programs, the reader is advised to refer to the 3-D rigid-lid User's Manual (Sengupta et al, 1980) prepared for this purpose. The calculations shown below were for February 27, 1979 simulations.

Reference Quantities Used

Reference length = L = maximum length of the domain = 2895.6 m.

Reference horizontal eddy viscosity $A_{ref} = 0.002\ L^{4/3} = 38311.48\ cm^2/sec.$

(Note: The constant '0.002' changes with different sites. This particular value was used in running the model at Lake Belews and at Biscayne Bay. In this case the best value of the constant was found to be '.003' which yielded a value of $A_{ref} = 60,000\ cm^2/sec.$

Reference depth = H = max depth considered = 16 m

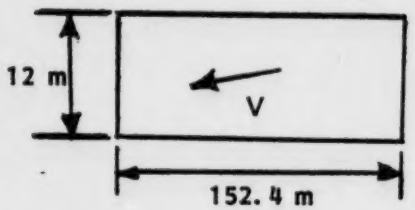
Reference vertical eddy viscosity $A_v = 0.002 \times H^{4/3} = 37.43\ cm^2/sec.$

Reference velocity $U_{ref} = 30\ cm/sec.$

Reference time $T_{ref} = L/V_{ref} = 9652\ sec.$

Oconee Nuclear Station Discharge Velocity

The discharge is considered to take place through a point at a depth of 12 m (k=3). The discharge velocity is calculated as follows.



The total discharge = $(100 \frac{cm}{m} \times V(\frac{cm}{sec}) \times 152.4 \times 12) = Q$

(where Q = average discharge in m^3/sec.)

$$\therefore V = 7.4207 \text{ cm/sec}$$

The average value of 'Q' over 24 hrs is taken since the variation is negligible.

Nondimensional discharge velocity = $\frac{V}{V_{ref}} = \frac{V}{30} = 0.24740.$

Keowee Hydro Discharge Velocity

The outflow through the Keowee hydro station is through a channel (152.4 m) x (12 m).

The volume flowrate Q = (152.4 x 12 x V) m^3/sec.

(where V = discharge velocity (m/sec.)

$$V = [Q/(152.4 \times 12)] \text{ m/sec} = \frac{Q}{152.4 \times 12 \times 100} \text{ cm/sec}$$

Q is specified as a function of time with the help of polynomials and other functions. The curve is approximated and specified in subroutine INLET1; (refer to the user's manual (Sengupta et al, 1980).

Keowee hydro flow approximation: refer to the user's manual (Sengupta et al, 1980).

(February 27 Data)

SX = Conversion factor for converting discharge (incfs) to nondimensional velocity.

SV1 = Nondimensional velocity.

The velocities are approximated as follows:

SV1 = 0.048 $\quad 0 \leq TSDT \leq 6$

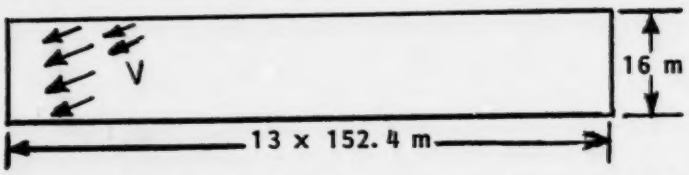
$$SV1 = SX * (((17.54 - 0.048)/2.) * (TSDT - 6.0) + 0.48) \qquad 6 \leq TSDT \leq 8$$

$$SV1 = SC * (((.048 - 17.54)/4.) * (TSDT - 8.0) + 17.54) \qquad 8 \leq TSDT \leq 12$$

$$SV1 = SX * (0.048) \qquad 12 \leq TSDT \leq 24$$

Jocassee Flow Velocity

The entire flow to or from the Jocassee-pumped storage station is assumed to take place through the entire upper boundary. The flow through this area is shown in the following figure.



The flow is assumed to be uniform over this area (i.e., equal flow velocities at all internal grid points within this area) and is assumed to take place simultaneously with the flow through Jocassee-pumped storage station.

$$V = Q/[(16 \times 13 \times 152.4) \times 100] \text{ cm/sec}$$

(Q = flow through Jocassee-pumped storage station (m^3/sec).)

Q is positive when Jocassee is generating (i.e., the flow is into the region of interest) and negative when pumping (i.e., flow out of the region of interest).

Jocassee flow approximation:

(February 27 Data)

TSDT = Time from start of run (hrs).

SV = Velocity of flow through Jocassee boundary (nondimensional).

SF = Conversion factor to convert flowrate (cfs) to nondimensional velocity

= 0.00322579

The velocity is approximated as follows.

$$SV = SF * (-14.395 - (18.75 - 14.395) * (TSDT) \qquad 1 \leq TSDT \leq 0$$

$$SV = SF * (-18.754) \qquad 1 \leq TSDT \leq 5$$

$$SV = SF * (((16.823 + 18.754)/3.) * (TSDT - 5.0) + 18.754) \qquad 5 \leq TSDT \leq 8$$

$$SV = SF * (((16.823 - 0.1)/3.) * (TSDT - 8.0) - 16.823) \qquad 8 \leq TSDT \leq 11$$

$$SV = SF * 0.1 \qquad 11 \leq TSDT \leq 23$$

$$SV = -SF * ((4.5 + 0.1) * (TSDT - 0.1) \qquad 23 \leq TSDT \leq 24$$

A similar procedure was followed for simulations of the other days.

Condition at Open Boundaries

Open boundaries are those where the values of temperatures and/or velocities cannot be specifically obtained but continuity of flow has to be maintained. One such boundary is at the mouth of the canal connecting the two arms of Lake Keowee. The condition $\frac{\partial}{\partial x} = 0$ is sepcified here both for velocities and temperatures. At the Jocassee and Keowee boundaries, the same kind of zero gradient conditions is specified for temperatures only. The calculation of parameters (T_E, TAU, etc.) for the surface boundary conditions are shown in Section 2.

SECTION 6

RESULTS AND DISCUSSIONS

The results of simulation using the 3-D rigid model at Lake Belews and Biscayne Bay are shown in previous publications by the University of Miami (Lee, Sengupta and Mathavan, 1977, and Lee and Sengupta, 1976). In the above two cases the predictions made by the model agreed closely with IR scanner and ground truth data. The following section discusses the runs made for Lake Keowee.

Preliminary Runs and Results

These runs were primarily made for the selection of the boundary conditions, initial conditions and to test the behavior of the model when incomplete and/or arbitrary data are used. These runs are summarized in Table 13.

1. Run Number L001

   (The Number L001 is a sequence number and must only be interpreted as such.)

   This run was essentially made for debugging the computer program modifications. The features include a discharge velocity of 5.65 cm/sec, a discharge temperature of 32.3°C and a 16 meter constant depth region of interest. The total simulated time was 20.6 hours. The results are summarized in Figures 18, 19 and 20. The surface velocities after 8.64 hours are shown in Figure 18, while Figure 19 shows the velocities in a vertical plant (I=11) after 21.6 hours. Since the effects of wind were not included in this run and there were no effects of Jocassee, the velocities are by the discharge velocity and the buoyant plume. The isotherm comparison of the archival run and this simulation run is shown in Figure 20. The ambient temperature is 29°C. The archival isotherms are higher than the predicted isotherms. This is expected since this run (without wind) was not undertaken primarily for comparison purposes, and the simulation did not reach steady state.

2. Run Number L002

   This run is similar to 'L001' but with variable depth of the region of interest. The simulation time was only 8.64 hrs. This time is long enough to determine how well the model handles a variable

depth domain. The surface velocities and vertical velocities (at I=11) are shown respectively in Figures 21 and 22. For completeness, the simulated surface isotherms are compared with the archival isotherms. This comparison is shown in Figures 23. For the same reason described in the previous subsection, the comparison cannot be expected to be more precise.

3. Run Number L003

Run L002 is now repeated with the effects of wind included. The total time simulated was only 8.00 hrs. The reason for the short simulation time is as explained above . The surface and vertical velocities (J=7) are shown in Figures 24 and 25 respectively. A comparison of Figures 21 and 24 shows the small effects of wind on the surface velocities after such a small simulation time. The wind speed is 4 m/sec. A comparison of the predicted and archival isotherms is shown in Figure 26. Compared with the other isotherm comparisons, this figure appears to have improved the difference between measured and predicted.

Archival Runs and Results

Two runs were made (L004 and L005) using the archival data base described in the last section.

1. Boundary Conditions

The following specifications were used at the main input boundaries.

a. At I=1, J=8 to 19 for all depths (K)

The water velocity at the Jocassee end is specified as 6.9 cm/sec. Open boundary is specified for temperatures as this end.

b. At I=11, J=1, K=3

This discharge velocity is specified as 5.65 cm/sec, and the dishcarge temperature also specified as 32.4°C.

c. Finally, at I=13, J=7, K=1 to 3

Keowee dam discharge velocity is specified as 10.4 cm/sec.

2. Run Number L004

This is the first archival run and was made with variable depth topography for the near-field region of interest.

3. Run Number L005

Run L004 is repeated but for constant depth region of interest. The domain was cut off at 16 meters from the water surface. This is the depth of the thermocline for Lake Keowee.

4. Archival Results

Figure 27 shows the comparison between the measured (archival 9/10/75) and calculated (L004) isotherms. The ambient temperature was 29°C. This comparison can be seen to have improved when compared to those of the preliminary runs already described. The surface velocities are similar to 'L005' which are shown in Figure 28. Flow through the Keowee dam can be seen very clearly on the right boundary of the figure. Figure 29 shows the velocity field at J=7, which also shows the flow through the Keowee dam. The isotherm comparisons of measured (9/10/75) and predicted (L005) is shown in Figure 30. This is the best comparison of the runs described so far. The agreement is particularly good for the 29.5 and 30°C isotherms. The shapes of the measured and predicted 30.5°C isotherms are similar. However, the measured area under the isotherm appears bigger. This discrepancy can be explained in terms of the nearness of this isotherm to the discharge. The total time simulated was 32.4 hrs, which is also the time when steady state was reached. The temperature profiles for locations I=11, J=7, K=1 to 4 through the simulated period are shown in Figure 31. The temperature profiles are vertical as expected since computations were carried out above the thermocline. A comparison of the surface velocities at this location is given in Figures 32. It can be seen from this figure that the u-component velocities predominate. It can also be seen from this figure that all the velocities stabilize after about 30 hours, showing steady state conditions. A similar plot, Figure 33, for the same variables but for location I=11, J=2 and K=1 is shown. Similar conclusions hold for this figure.

L001 through L005 were archival runs. The following section discusses the results of simulations for the August data base (L006) and February data base (L007). Both these runs were made in stabs of 24 hrs of simulation at a time for a total period of 48 hours of simulation in each case. Results were stored and printed at the end of every hour of real time. The results at the end of the first 24 hrs simulation were used as initial conditions for the next 24 hrs.

Summer Runs

Simulation was started from 0000 hrs August 24. The model was started 'cold' i.e., initial conditions used were zero velocities and constant temperature (29°C) throughout the domain. This conditions required that the model had to be run for sometime before the effects of the cold start could be ignored.

The inputs used in running the model have been discussed in the

previous section. The wind speed driving the upper layer varied from 0.76 to 3.09 m/sec. The current or the flow through the Jocassee boundary varied from 0.61 to 1.12 cm/sec. The Oconee nuclear station discharge velocities and temperature were 7.42 cm/sec and 31.7°C respectively. (Average values were taken since the fluctuation was negligible.) All the above data were fed in every hour in running the model.

The surface isotherms and velocities at each horizontal section (K=1, 2, 3, 4 and 5) were plotted using a Calcomp plotter. Results at the end of each hour were stored and plotted. The results used for comparison were the surface isotherms plots. Measured surface isotherms were obtained from IR scanner digicolor maps. By drawing both the data and the predicted values on the same grid system direct comparison could be made.

The first IR runs were made on August 24 from 0853 hrs EST to 1002 hrs EST. The isotherms drawn for this data are shown in Figure 34. The isotherms shown are for 30.5°C, 30.0°C and 29.5°C. Only the above three isotherms fell within the domain of interest and represent the water surface temperatures at 1002 hrs EST, August 24, 1978. The results produced by the model are shown in Figure 35 and 36. Figure 35 shows the same isotherm i.e., 30.5°C, 30.0°C and 29.5°C corresponding to 1007 hrs real time. It is seen that the temperatures predicted by the model are lower than the actual temperatures, showing that the plume spread was underpredicted. Figure 36 shows different predicted isotherms corresponding to the same time. The temperatures of the isotherms are 29.5°C, 29.3°C and 29.1°C. Comparing Figure 36 with 34 it is seen that 29.5°C in the IR data agrees very well with the 29.1°C isotherm predicted by the model. The measured 30.5°C and 30.0°C isotherms compared with the predicted 29.5°C and 29.3°C isotherms respectively. Hence, the errors in prediction in the three isotherms (30.5°C, 30.0°C and 29.5°C measured) are approximately 1°C, 0.7°C and 0.4°C respectively.

The IR digicolor map for the August 24 afternoon data could not be used to construct isotherms because of bad resolution between different colors. Hence, the next useful comparison was made for the August 25 morning data (0903-9553 hrs EST). The IR isotherms are shown in Figure 37. The same three temperatures, namely 30.5°C, 30.0°C and 29.5°C, are represented here since the other isotherms lie beyond the domain of interest. Figure 38 shows the same isotherms as predicted by the model. The spread of the 29.5°C isotherm is overpredicted while the 30.0°C isotherm is underpredicted. However, Figure 39 shows isotherms for 29.90°C, 29.70°C and 29.6°C as predicted by the model. These isotherms compare very well with the IR isotherms in Figure 37. The errors in this case are .6°C for the 30.5°C isotherm, 0.3°C for the 30.0°C isotherm and -.1°C for the 29.5°C isotherm. This shows a considerable improvement in the predictions as compared to August 24, showing the effects of cold start gradually vanishing.

Figure 40 shows the plot of the horizontal velocities of the surface as predicted by the model for 1007 hrs, August 24. During this time (1007 hrs EST), as can be seen from the Jocassee-pumped storage station flow and Keowee hydro station flow data, the flows through these stations were negligible. This leads to zero velocities at Jocassee boundary and zero velocity through the Keowee hydro discharge point in Figure 40.

Figure 41 shows the surface horizontal velocities predicted by the model for August 25 (33.2 hrs run time). During this time (approximately 1000 hrs, August 25) Jocassee-pumped storage station just started generating and Keowee hydro was generating. This accounts for the flows through the two boundaries.

The main driving forces responsible for determining the shape of the isotherms are the ambient temperature, discharge temperature and flows through the Jocassee boundary. The wind is seen to affect the velocities in the upper layer only. This characteristic is displayed both in the data and the simulation results, Figure 34 (August 24 IR data) and Figure 37 (August 24 IR data). Looking at the Jocassee and Keowee flows it is seen that the flow through Jocassee is negligible during both these periods. The flow through Keowee is negligible at 10.00 a.m. on August 24 but is 9352 cfs on 10 a.m., August 25. The average discharge temperature is also lower on August 25 as compared to August 24. This causes the area under the isotherms in Figure 37 to be lower than those in Figure 34. The same difference is seen between the corresponding predicted isotherms, namely Figure 36 (August 24, 1978) and Figure 39 (August 25).

Winter Runs

Simulation was started from (0000 hrs) February 24, 1979. The model was started using zero velocities and constant temperature (= 10°C) as initial conditions.

The inputs used for this run (L007) have been discussed in detail in previous sections. The Oconee discharge velocity (average value) was 6.84 cm/sec and the discharge temperature (average value) was 18.4°C. The wind speed varied from 1.61 to 4.52 m/sec and the Jocassee-pumped storage station boundary flow velocity ranged from 0.61 to 4.14 cm/sec.

Values of velocities and temperatures were printed at the end of every hour. Surface isotherm plots and velocity plots were generated from these results. Figure 42 shows the IR scanner isotherms for 1648-1651 hrs, February 27. The temperatures are 13.0°C, 12.5°C, 12.0°C, 11.5°C and 11.0°C. The same isotherms as predicted by the model are shown in Figure 43. These correspond to 17.12 hrs after the cold start. Comparing these two figures it is seen that the isotherms predicted by the model have a greater spread. Figure 44 shows predicted isotherms corresponding to 13.75°C, 13.0°C, 12.75°C, 12.5°C and 12.0°C.

This figure agrees better with Figure 42 showing an error of prediction of 0.75°C, 0.5°C, 0.75°C and 1°C respectively for each of the isotherms.

Figure 45 shows IR scanner isotherms for February 28, 1979 corresponding to 0948-0957 hrs EST. The two isotherms within the domain are for 13.0°C and 12.5°C. Figure 46 shows the same two isotherms as predicted by the model. These correspond to 34.2 hrs of run time after the cold start at approximately 10 a.m., February 28. Figure 46 is in excellent agreement with Figure 45. Isotherms for IR data corresponding to February 28 afternoon could not be drawn because of bad resolution among different colors in the digicolor map.

Figure 47 shows velocities at the surface as predicted by the model for February 27, 17.12 hrs after the cold start. The flows through the Jocassee and Keowee hydro boundaries agree with the data obtained. Figure 48 shows the same for February 28, 34.2 hrs after cold start. Excellent agreement is obtained in this case between the velocities shown on the map and measured flows at Keowee hydro station and Jocassee-pumped storage station. As in one of the summer runs, the isotherms are affected by the Oconee discharge, Keowee hydro and Jocassee-pumped storage station. Figures 42 and 45 (isotherms for February 27 and 28 respectively) show that the isotherms have spread out further on the second date. Keowee hydro and Jocassee-pumped storage station flows are negligible on both the dates. The average Oconee discharge temperature during 1600 hrs, February 27, was lower than that during 1000 hrs, February 28. This accounts for the greater spread of the isotherms. The same is depicted in the results produced by the model.

REFERENCES

Duke Power Company. Oconee Nuclear Station Thermal Plume Study. 1978.

Duke Power Company. Oconee Nuclear Station Thermal Plume Study. 1979.

Duke Power Company. Oconee Nuclear Station Environmental Summary Report, 1971-1976. 1976.

Freeman, N. G., Hale, N. G. and M. B. Danard. A Modified Sigma Equations Approach to the Numerical Modelling of Great Lakes Hydrodynamics. J. Geo. Res., Vol. 77, No. 6. 1972.

Haq and W. Lick. The Time-Dependent Wind-Driven Flow in a Constant Depth Lake. Presented at the 16th Conference on Great Lakes Research, Huron, Ohio. 1973.

Sengupta, S. and W. Lick. A Numerical Model for Wind-Driven Circulation and Temperature Fields in Lakes and Ponds. 1974. FTAS/TR-74-98.

Sengupta, S., Lee, S. S. and R. Bland. Numerical Modelling of Circulation in Biscayne Bay. Presented at the 56th Annual Meeting of the American Geophysical Union, 1975. Appeared in Transactions of the American Geophysical Union, June 1975.

Sengupta, S., Lee S. and S. K. Mathavan. Three-Dimensional Numerical Model for Lake Belews. 1977. NASA Contract NAS10-9005.

Sengupta, S., Lee, S. and E. V. Nwadike. Verification of One-Dimensional Numerical Model at Lake Keowee. 1980. NASA Contract NAS10-9410.

Sengupta, S., Lee, S., Nwadike, E. V. and S. K. Sinha. Verification of Three-Dimensional Rigid Model at Lake Keowee. 1980. NASA Contract NAS 10-9410.

Wilson, B. W. Note on Surface Wind Stresses Over Water at Low and High Wind Speeds. Journal of Geophysical Research, Vol. 65, No. 10. 1960.

Young, D., Liggett, J. A. and R. H. Gallagher. Unsteady Stratified Circulation in a Cavity. J. of Engrg. Mechanics Div. ASCE. December 1976.

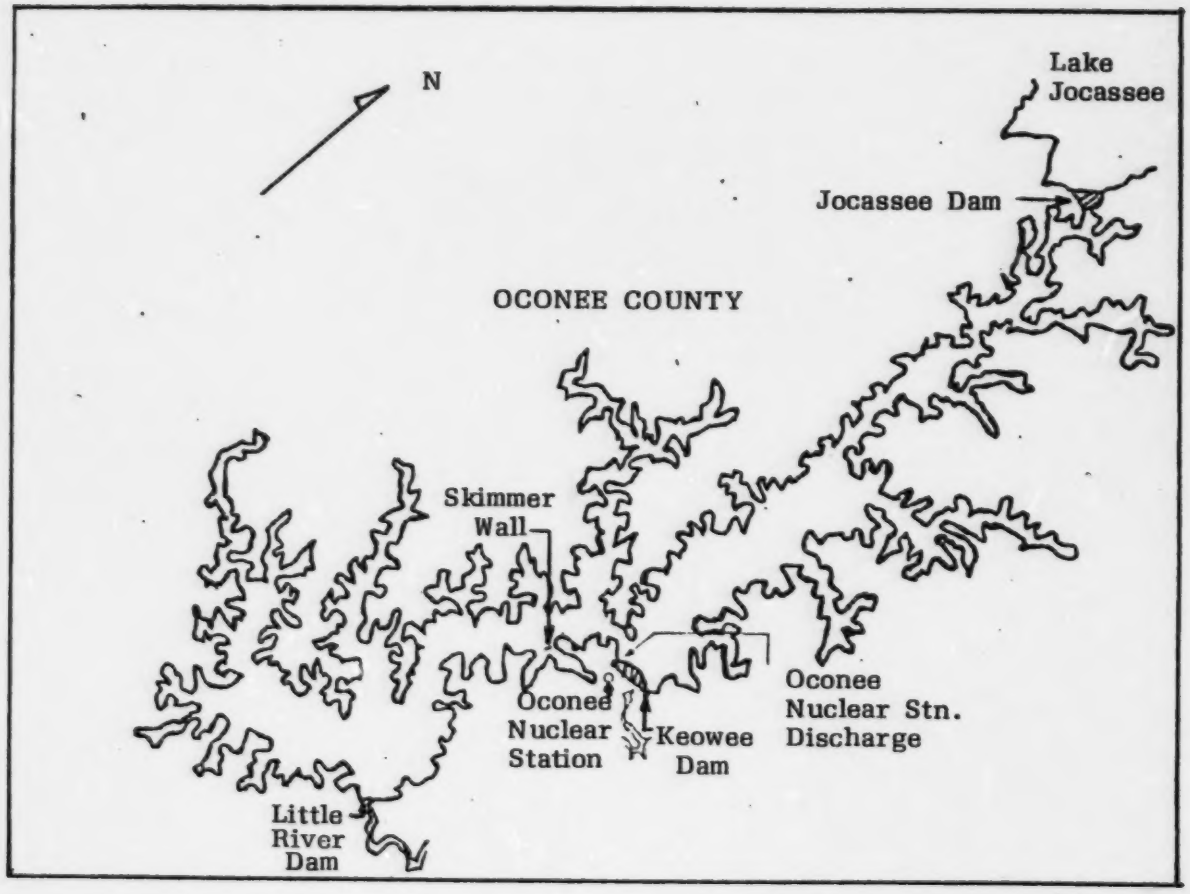


Figure 1. Lake Keowee

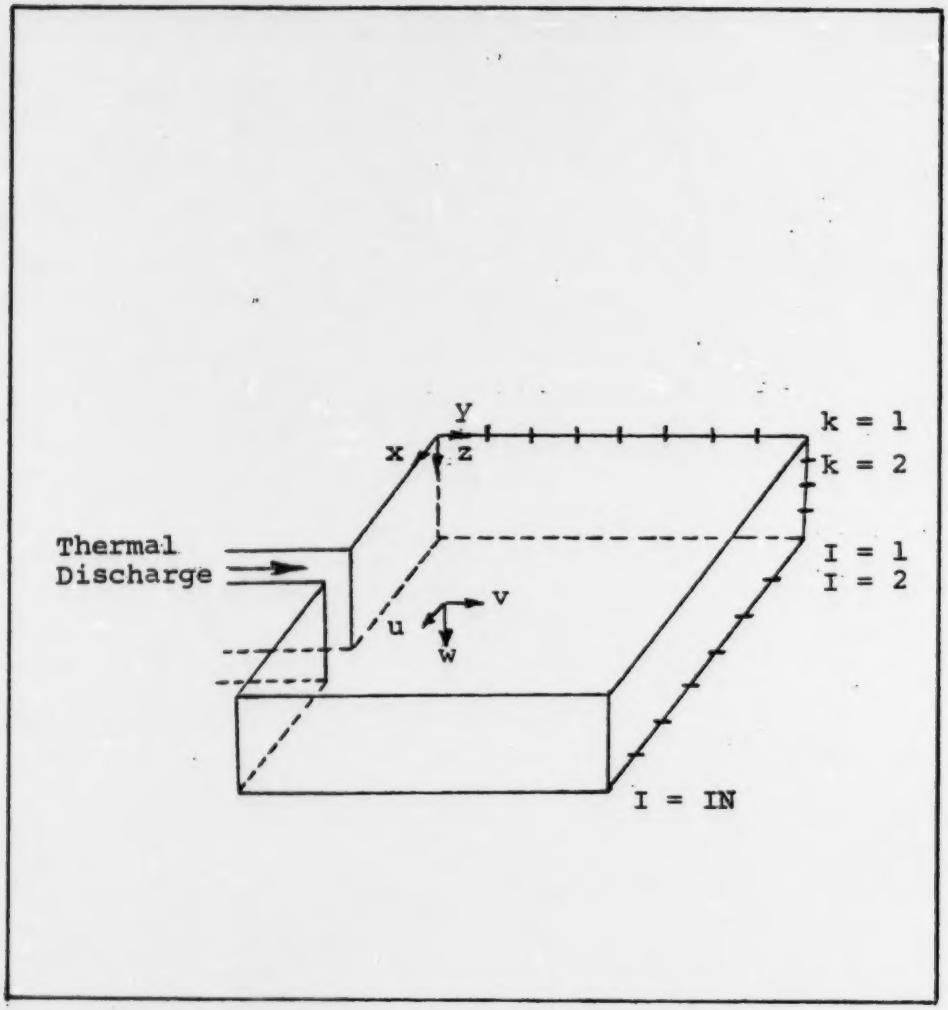


Figure 2. Coordinate and grid system

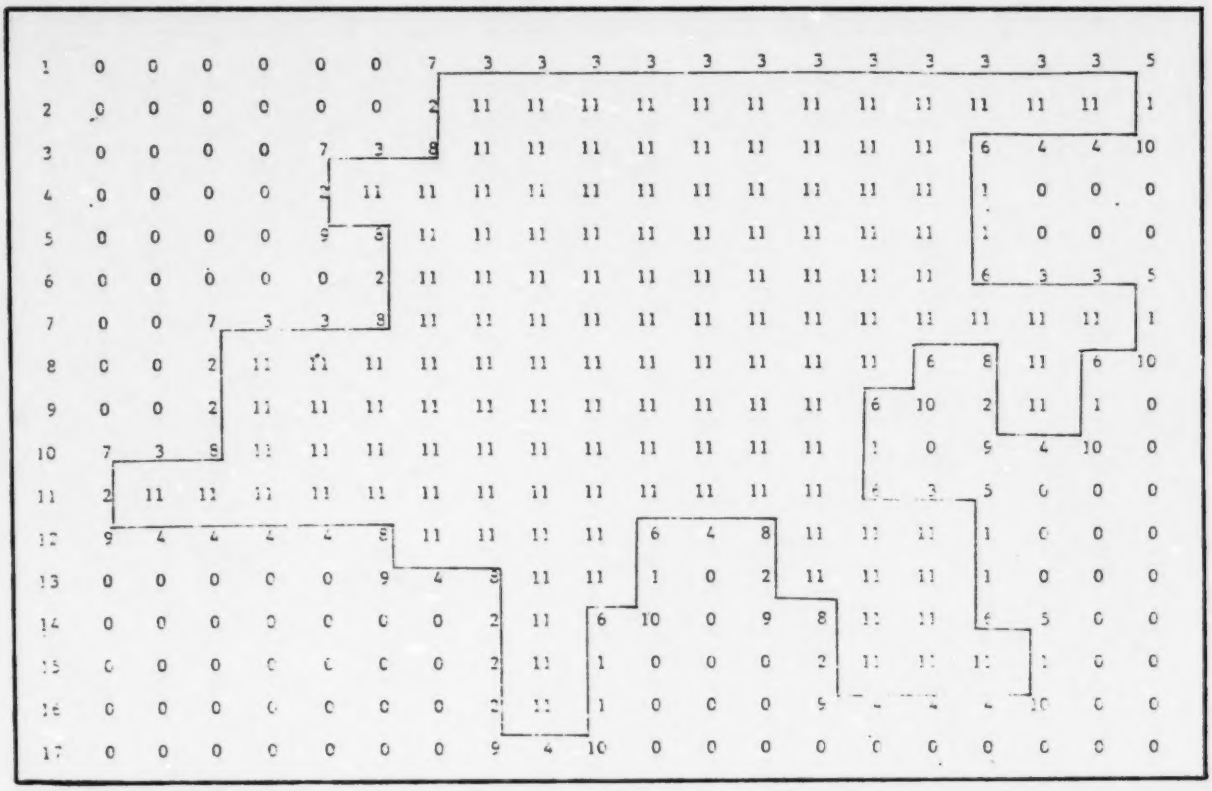


Figure 3. MAR marker matrix (main grid points)

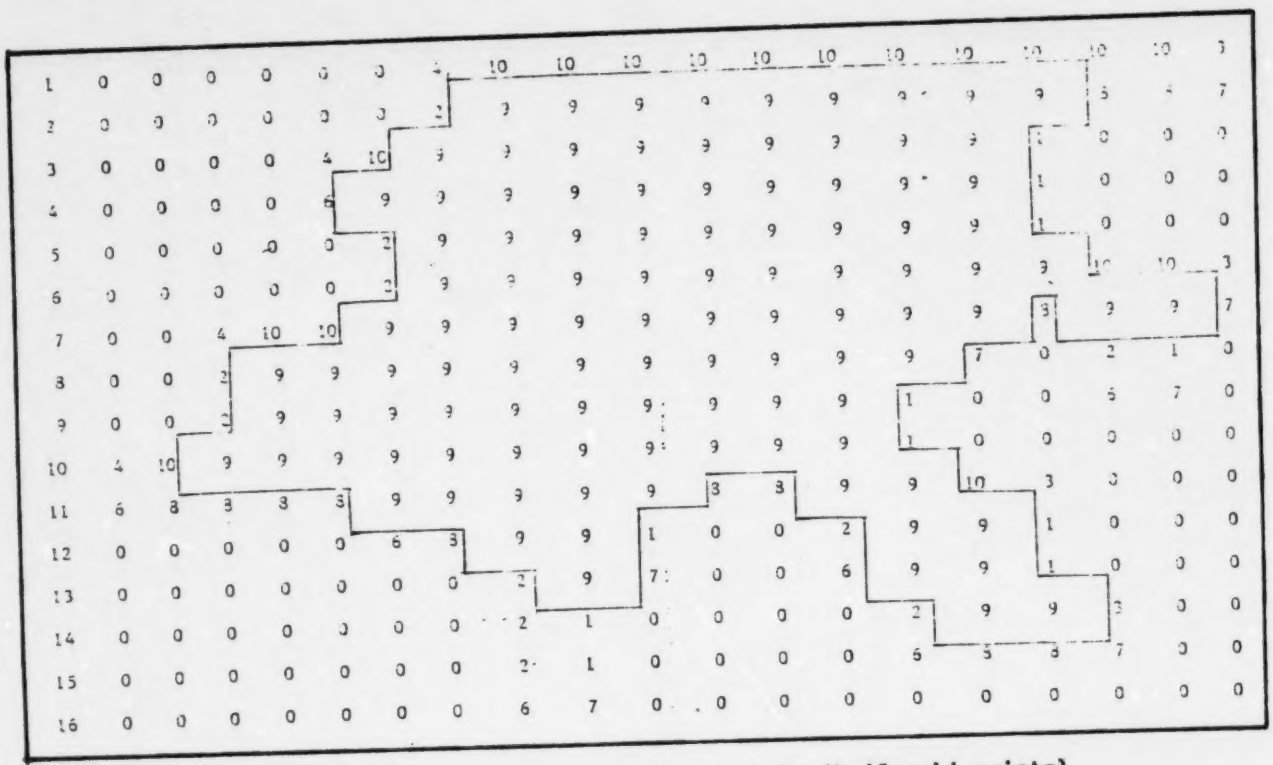


Figure 4. MRH marker matrix (half grid points)

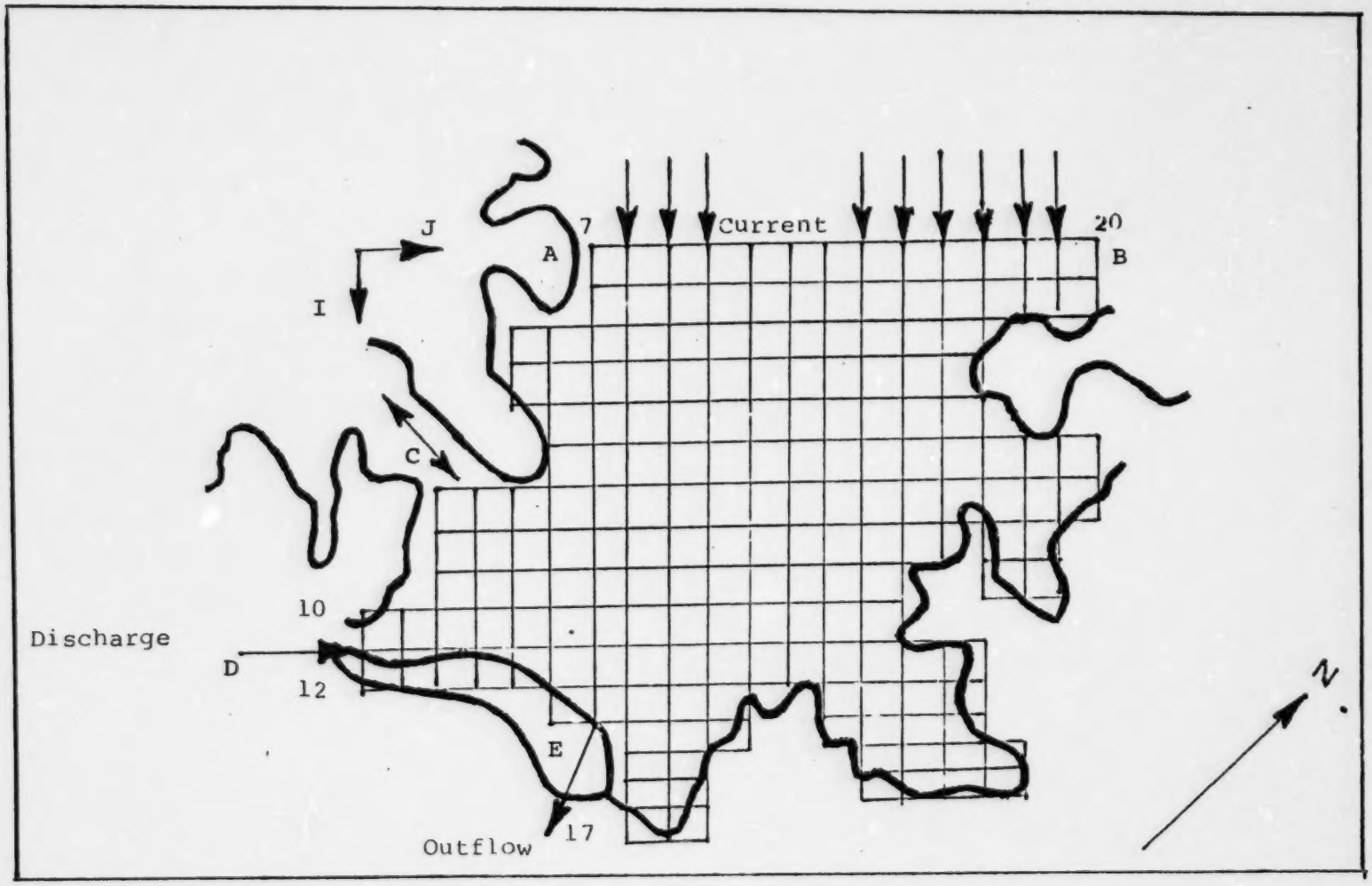


Figure 5. Lake Keowee (region of interest) showing inputs and outputs (for 3-D model)

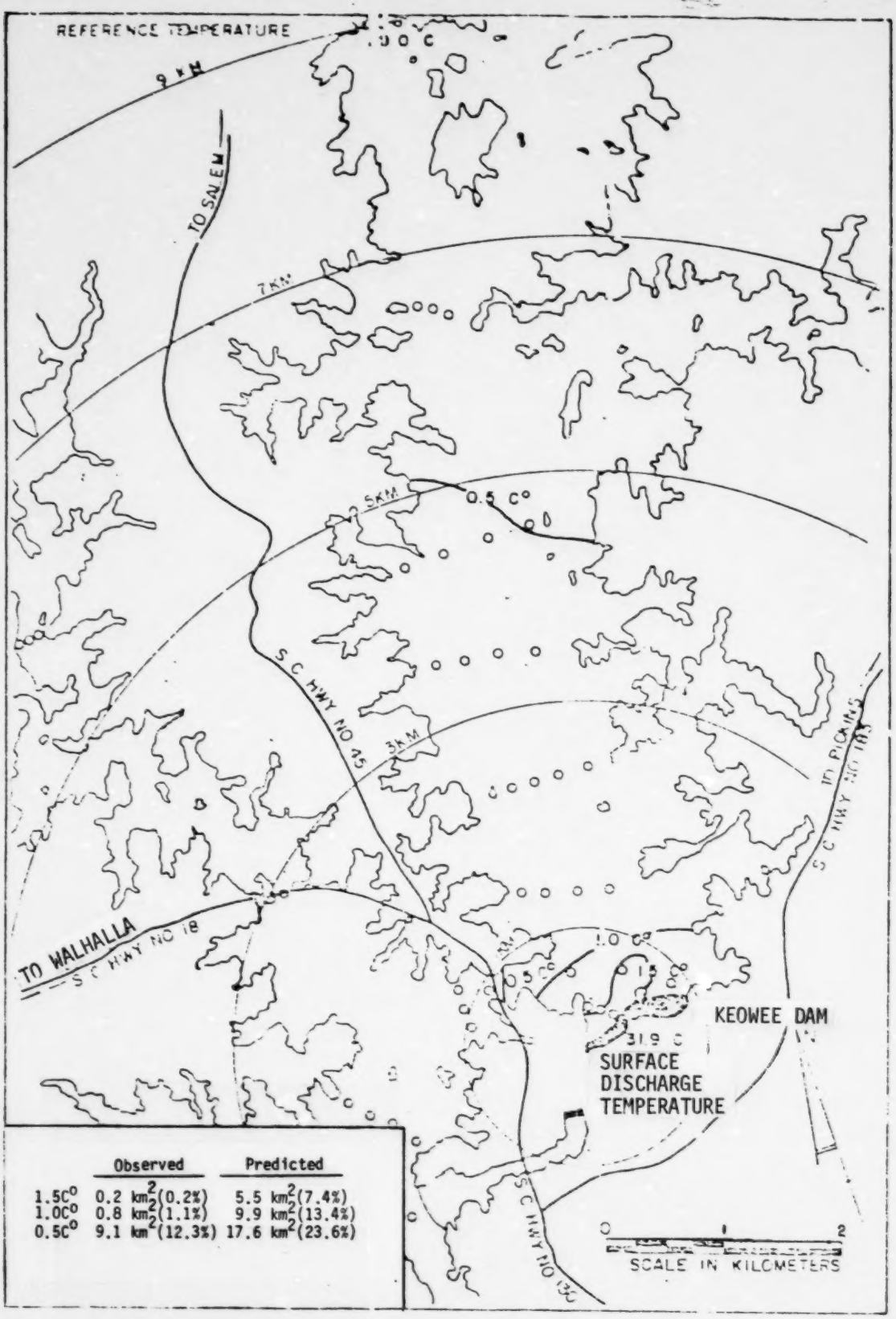


Figure 6. Measured isotherms (Archival 9/10/75)

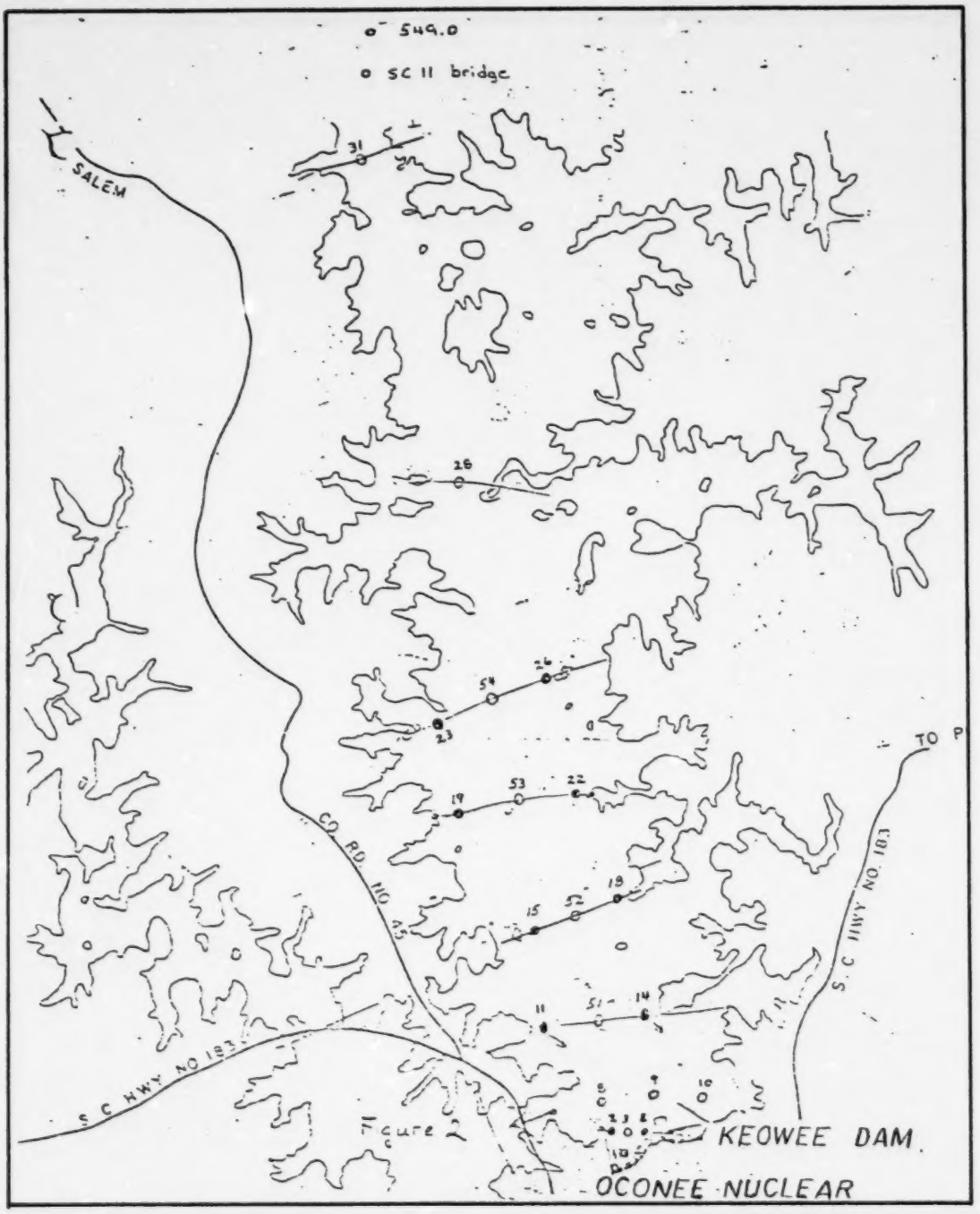


Figure 7. August ground truth data (measuring stations)

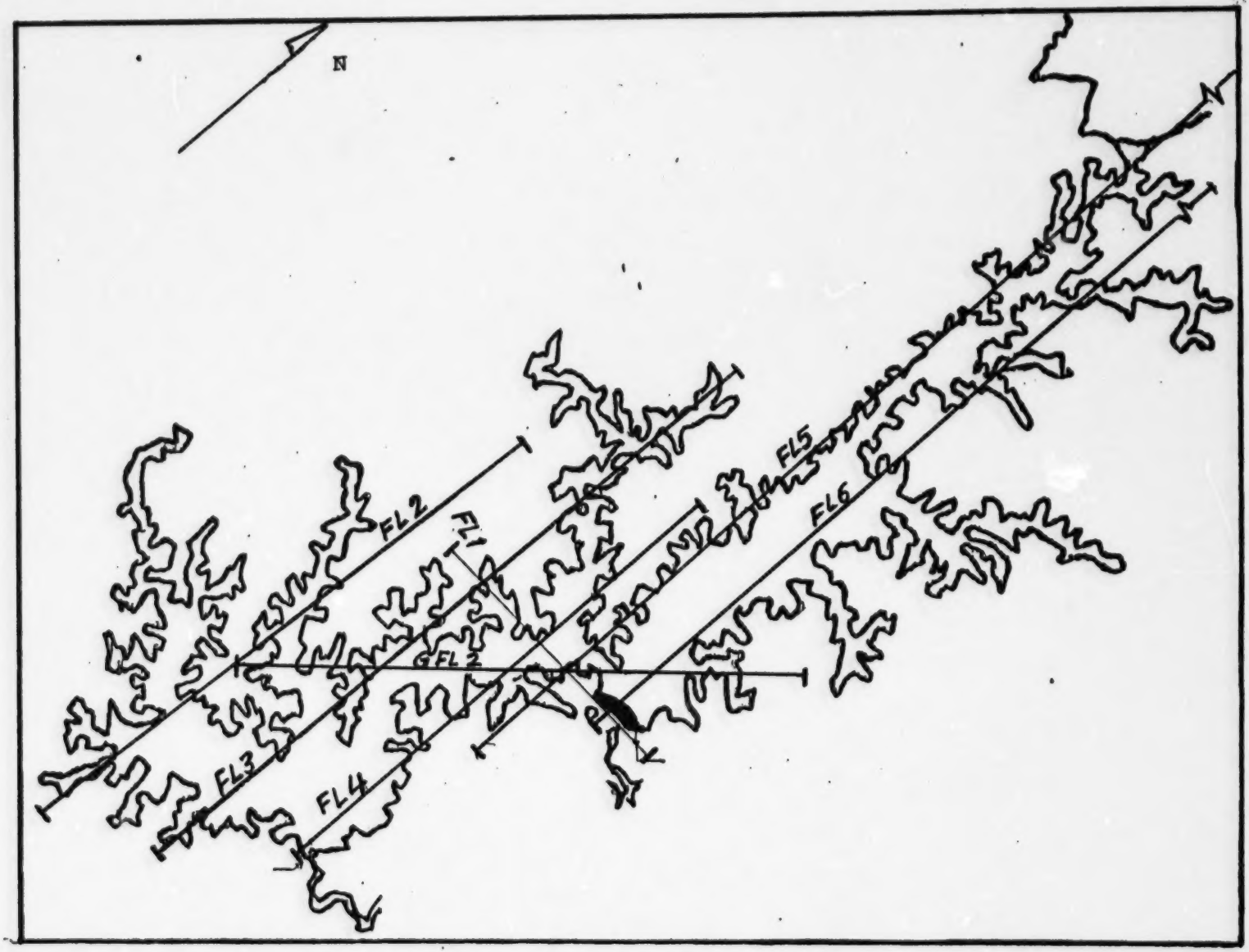


Figure 8. Flight plans for IR data (August and February missions)

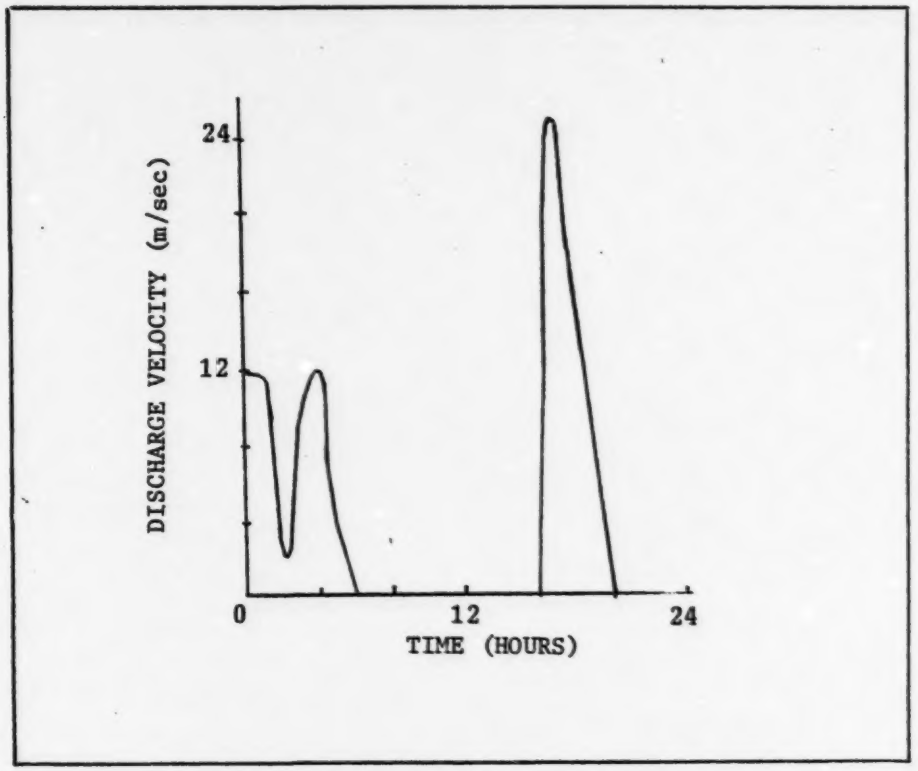


Figure 9. Keowee hydro discharge data (August 24, 1978)

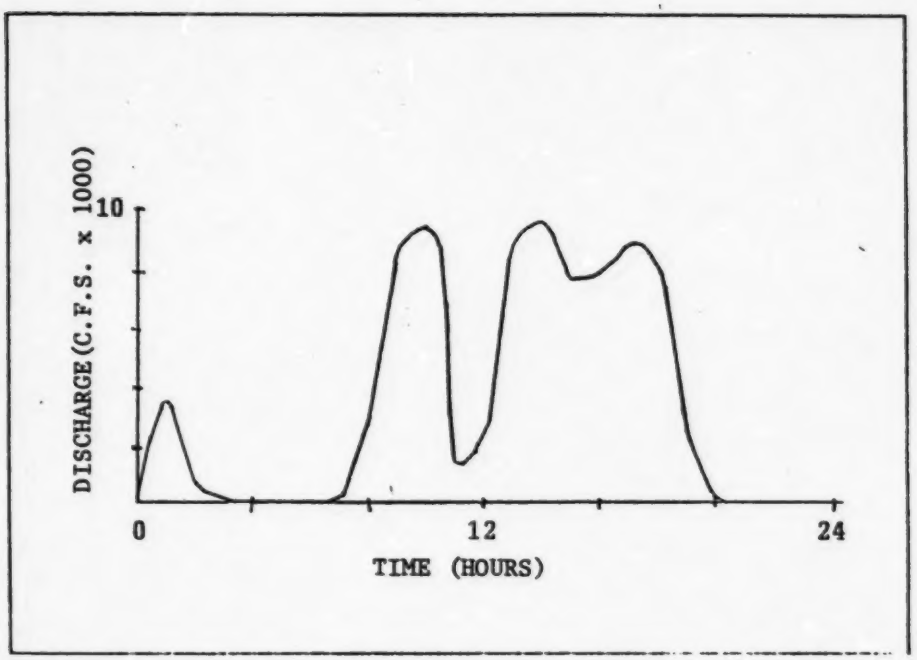


Figure 10. Keowee hydro discharge data (August 25, 1978)

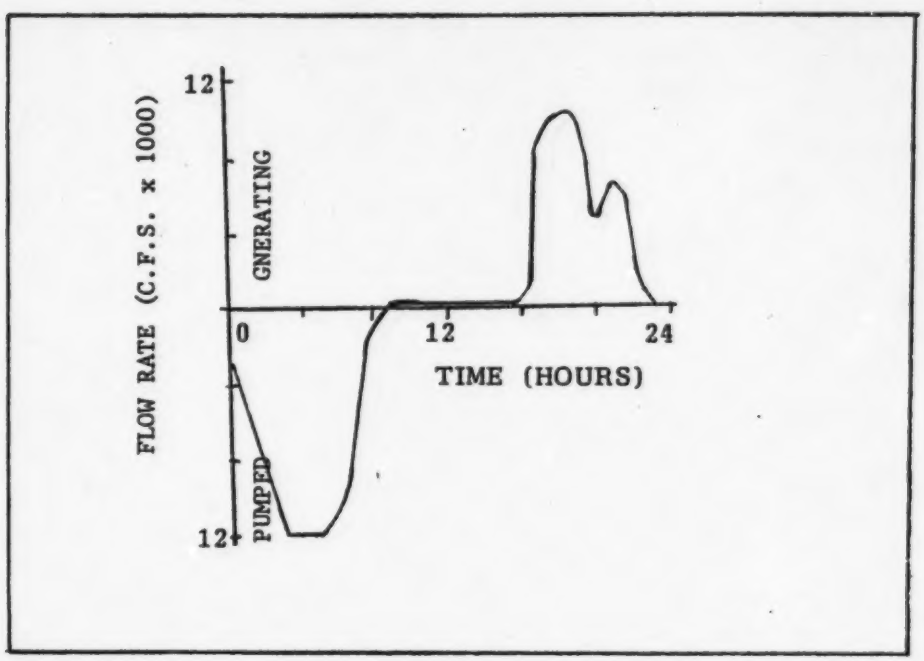


Figure 11. Jocassee-pumped storage station discharge data (August 24, 1978)

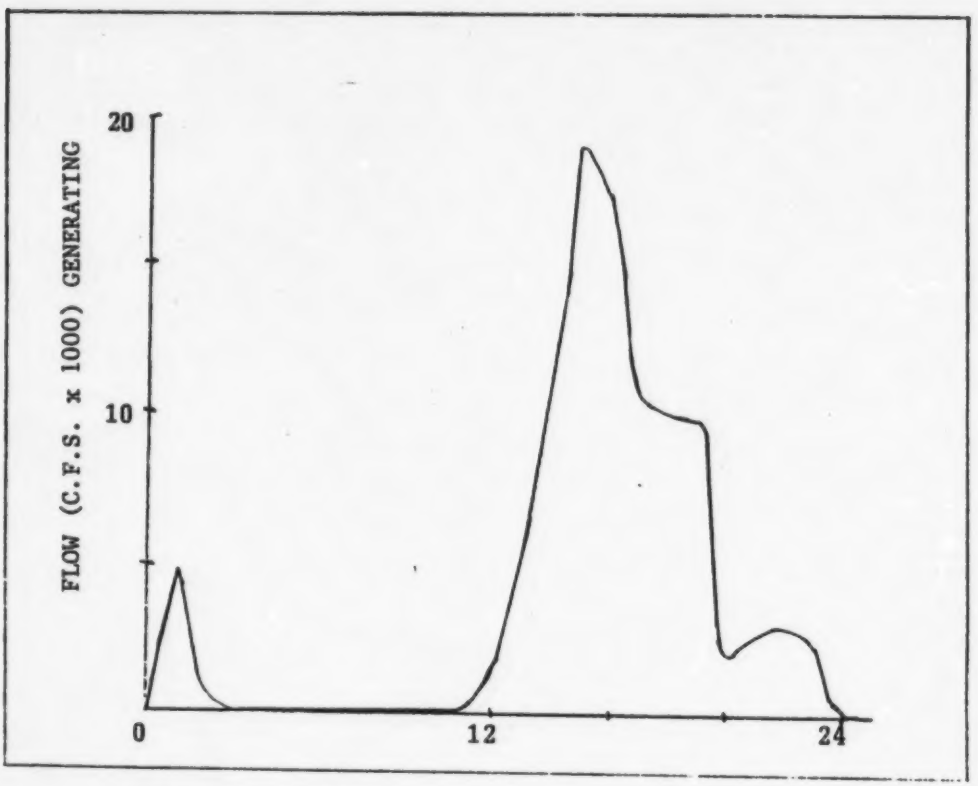


Figure 12. Jocassee-pumped storage station data (August 25, 1978)

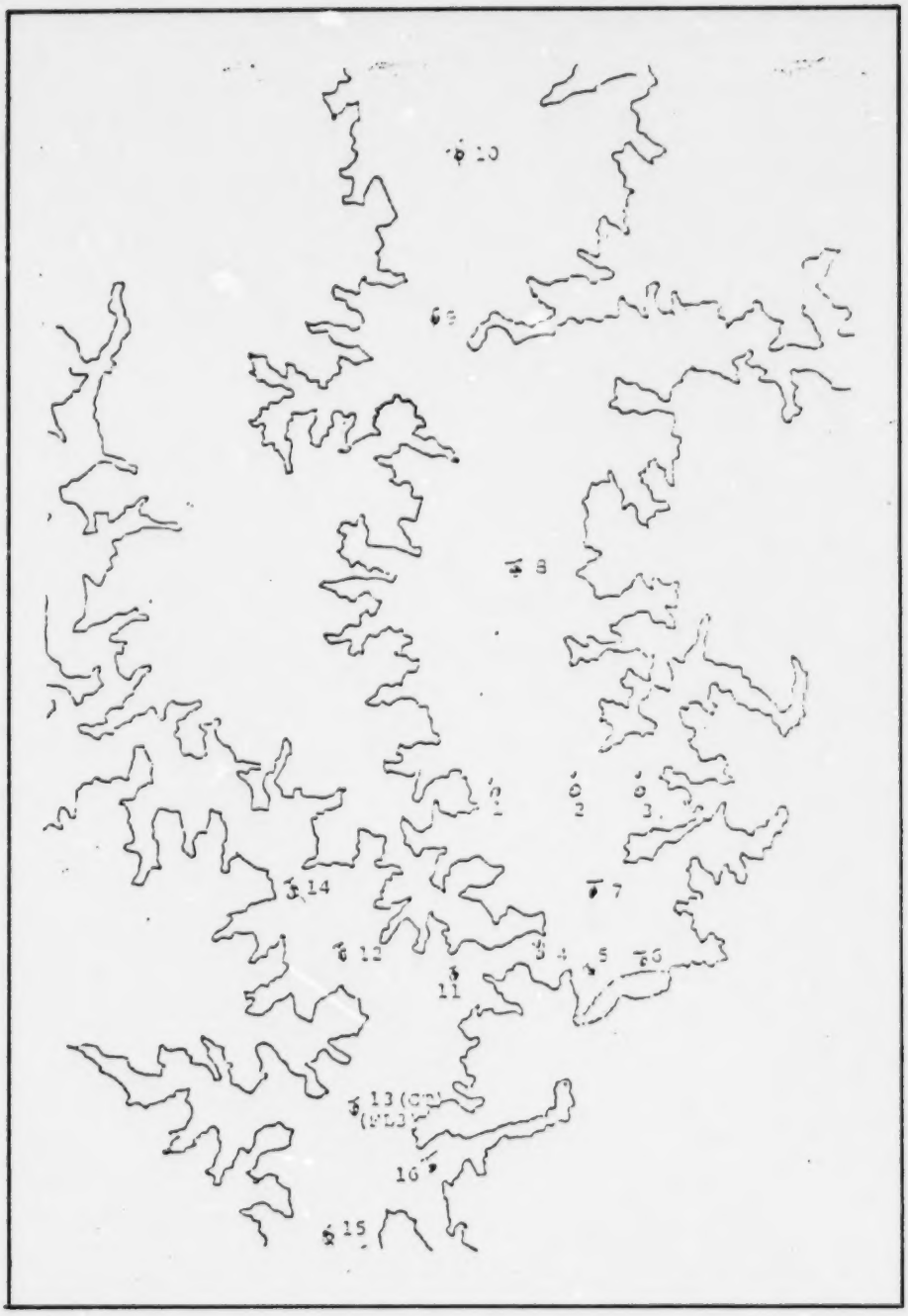


Figure 13. Keowee February 1979 mission showing stations (GT = groundtruth, FL3 = flight NoFL3)

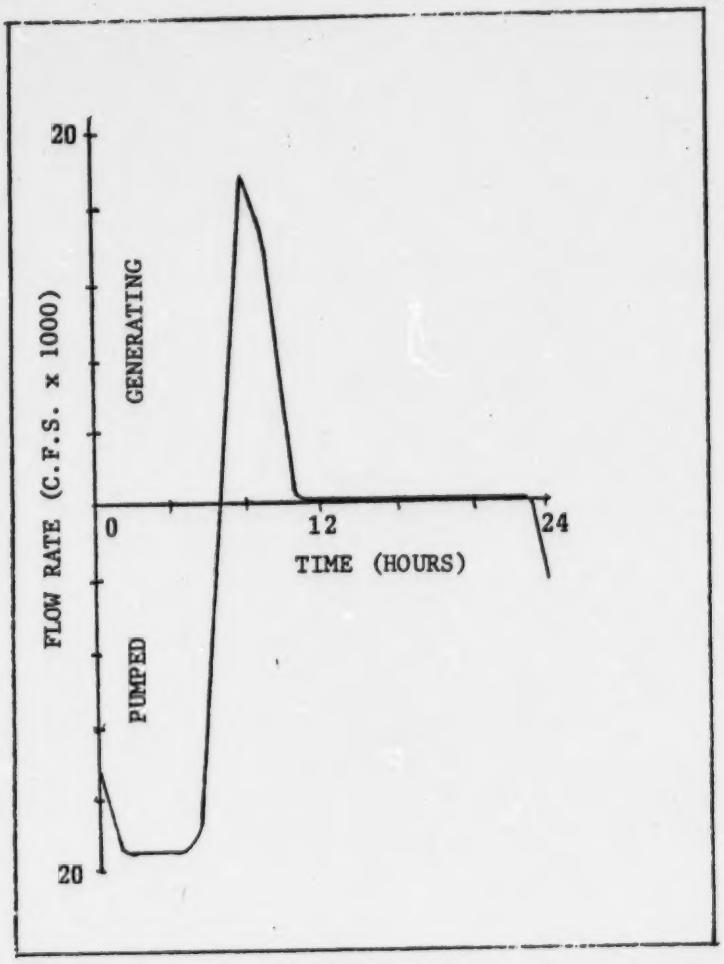


Figure 14. Jocassee-pumped storage station discharge data (February 27, 1979)

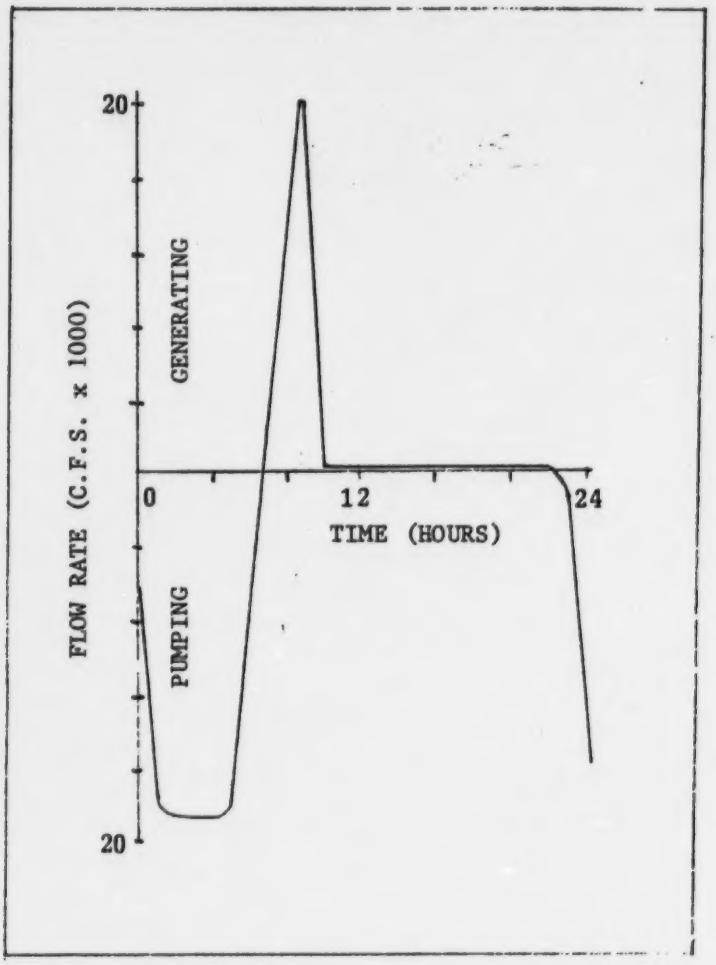


Figure 15. Jocassee-pumped storage station discharge data (February 28, 1979)

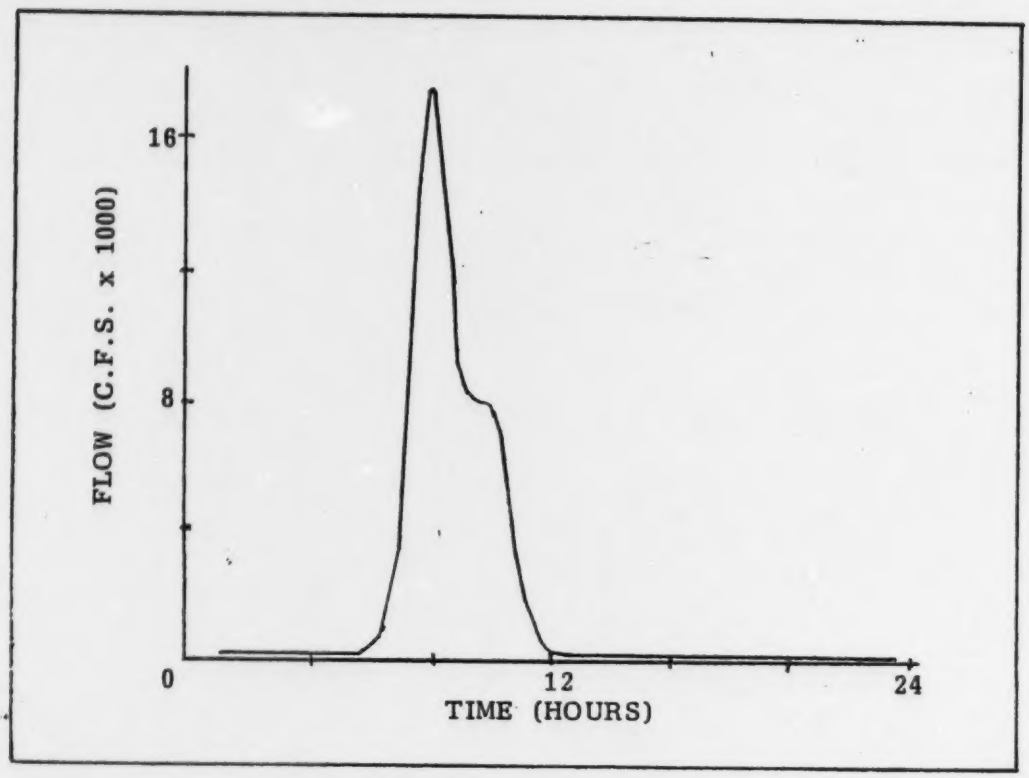


Figure 16. Keowee hydro discharge (February 27, 1979)

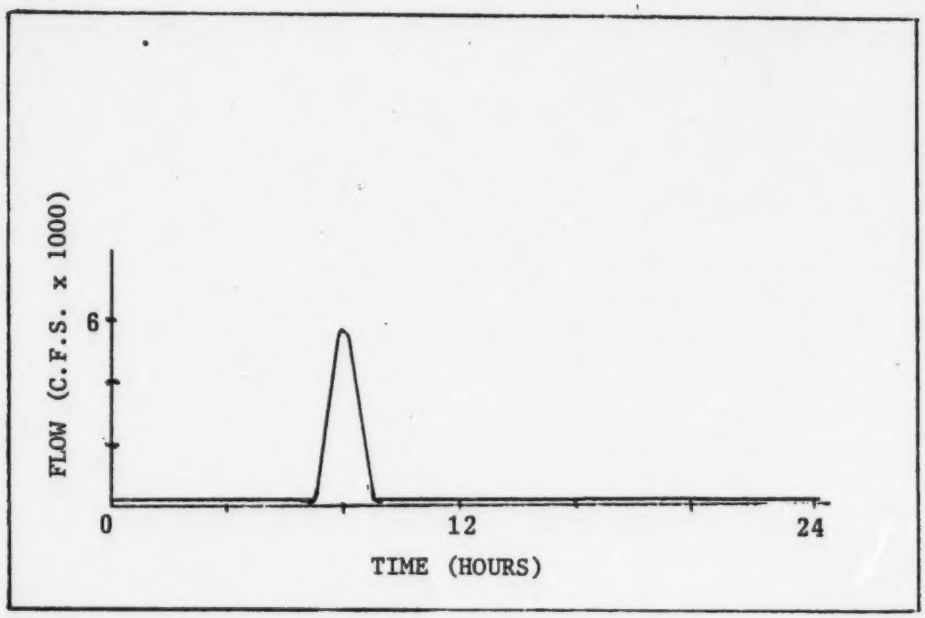


Figure 17. Keowee hydro discharge data (February 28, 1979)

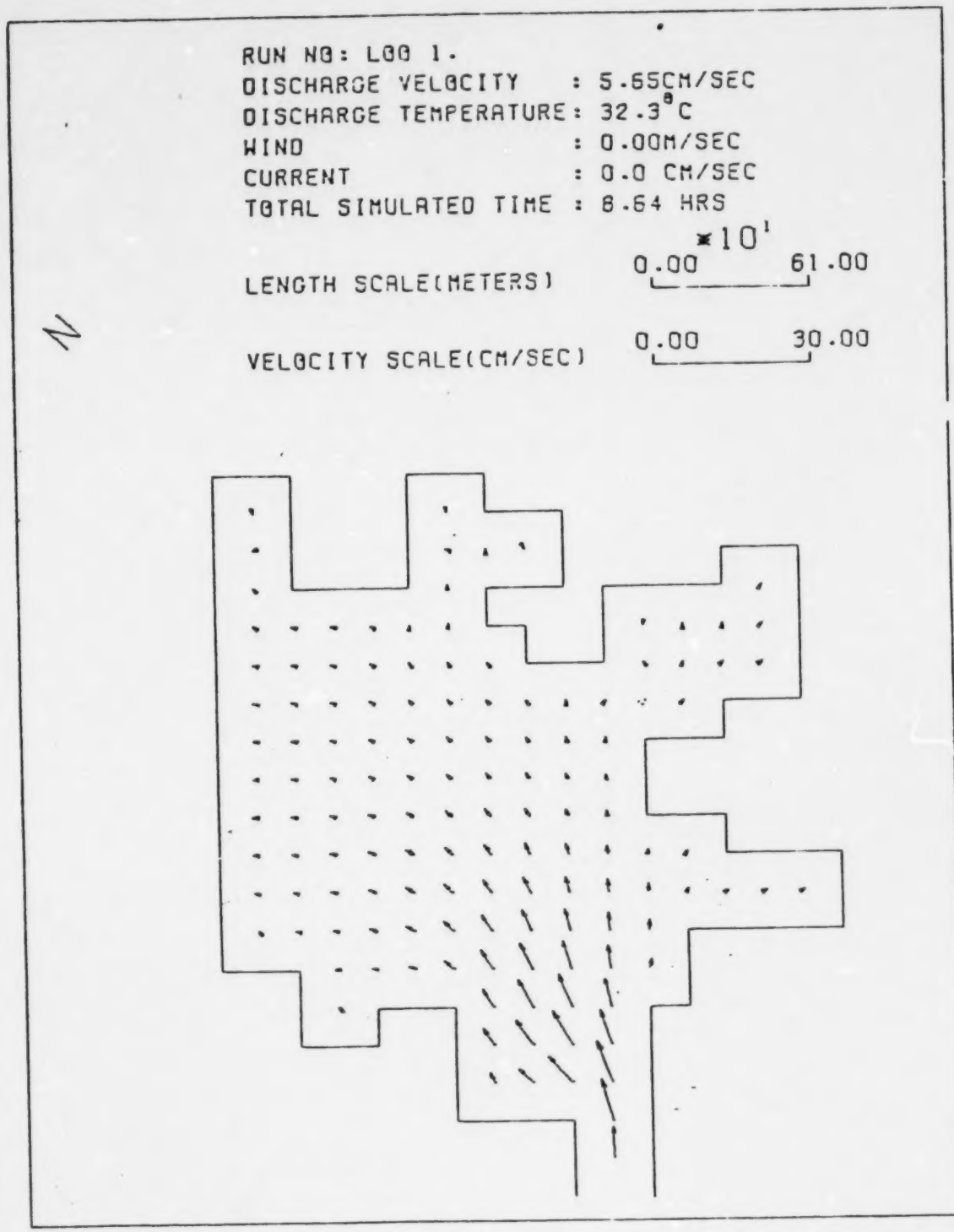


Figure 18. Velocities at K = 1, Lake Keowee (rigid-lid model)

RUN NO: L001.
DISCHARGE VELOCITY : 5.65CM/SEC
DISCHARGE TEMPERATURE: 32.3°C
WIND : 0.00M/SEC
CURRENT : 0.0 CM/SEC
TOTAL SIMULATED TIME : 21.60HRS

SCALES (HORIZONTAL)

LENGTH SCALE(METERS) ×10¹ 0.00 61.00

VELOCITY SCALE(CM/SEC) 0.00 12.00

SCALES (VERTICAL)

LENGTH SCALE(METERS) 0.00 20.00

VELOCITY SCALE(CM/SEC) 0.00 6.00

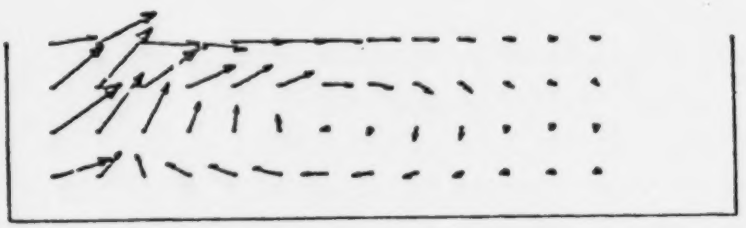


Figure 19. Velocities at I = 11, Lake Keowee (rigid-lid model)

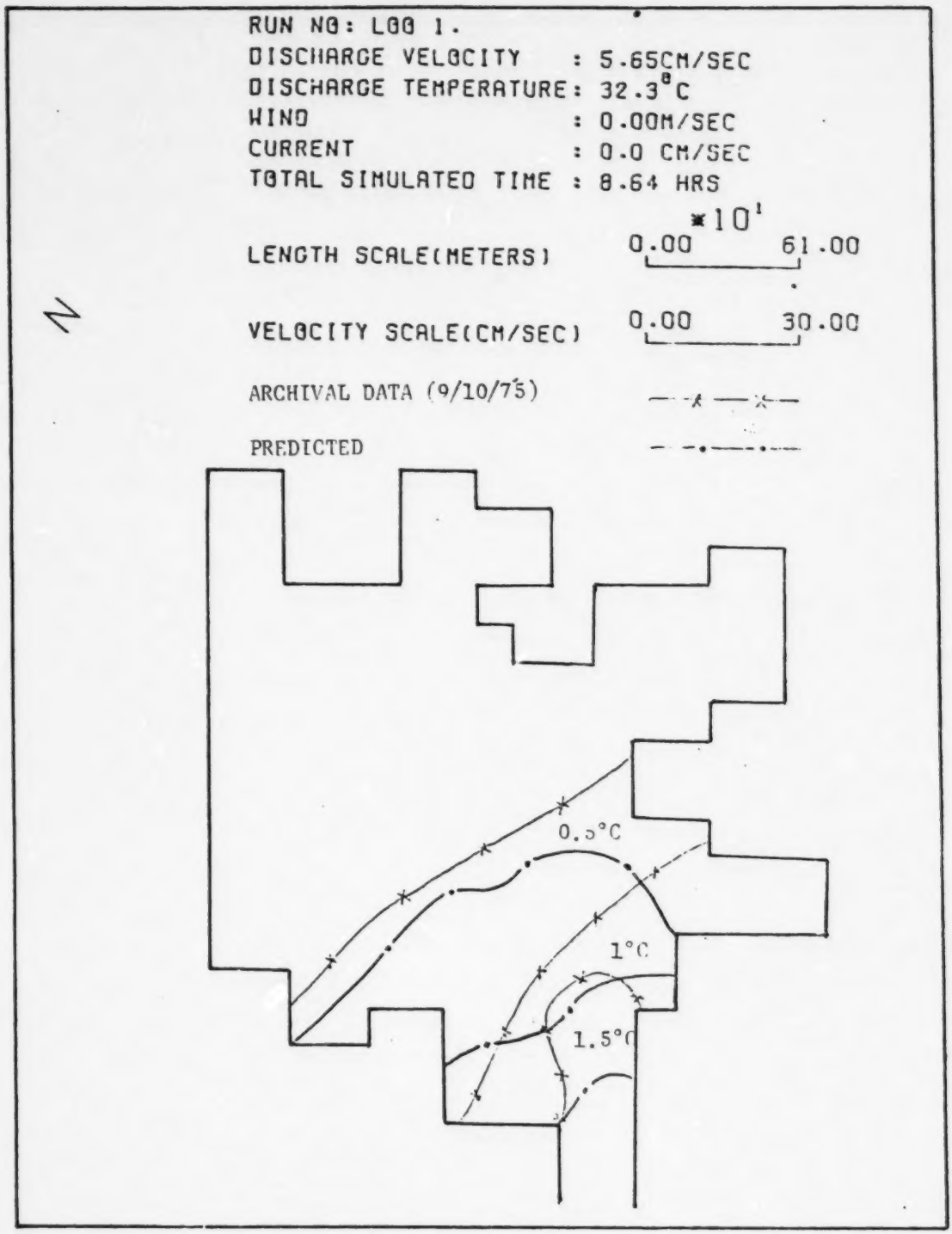


Figure 20. Isotherms: measured and predicted (temperatures above ambient)

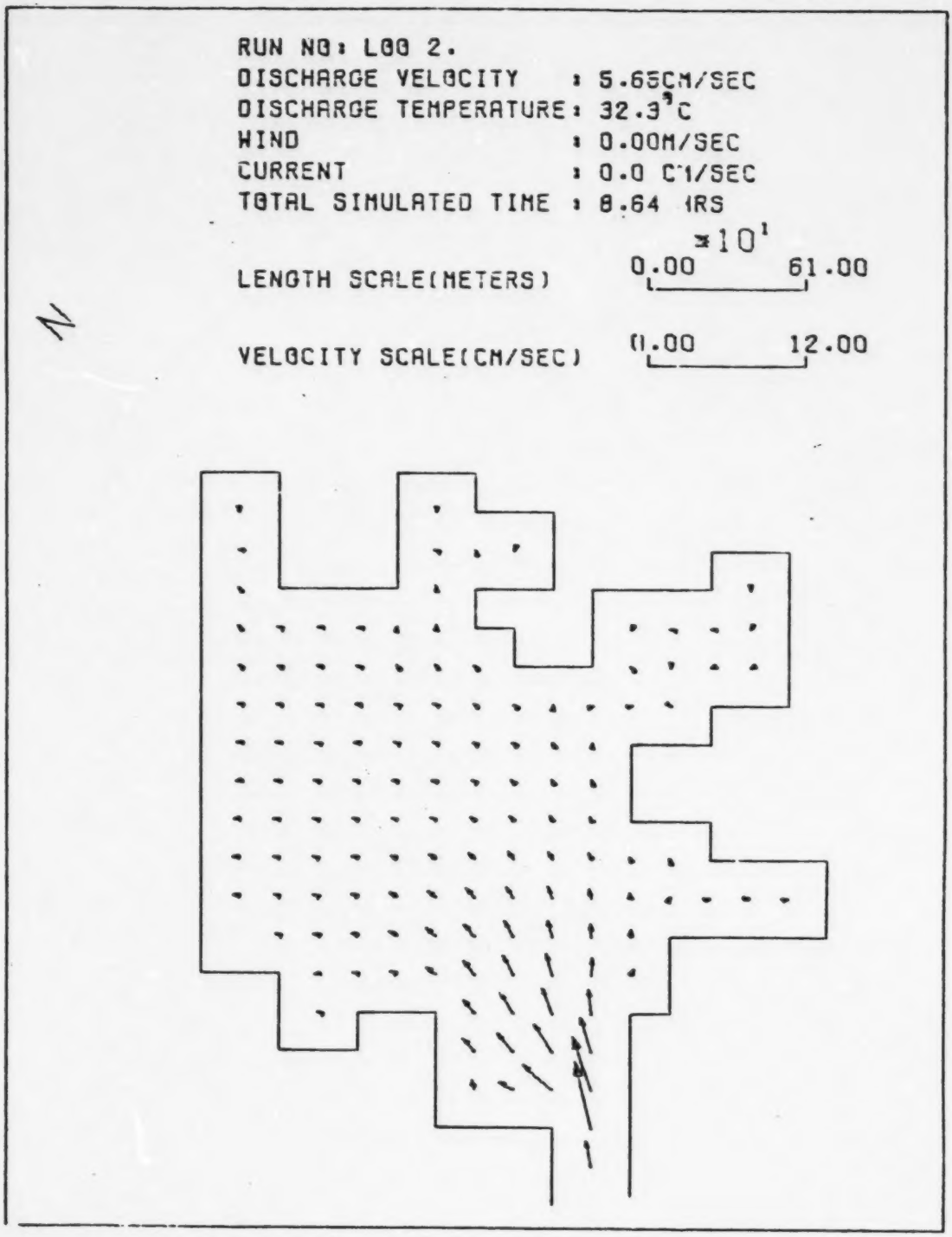


Figure 21. Velocities at K = 1, Lake Keowee (rigid-lid model)

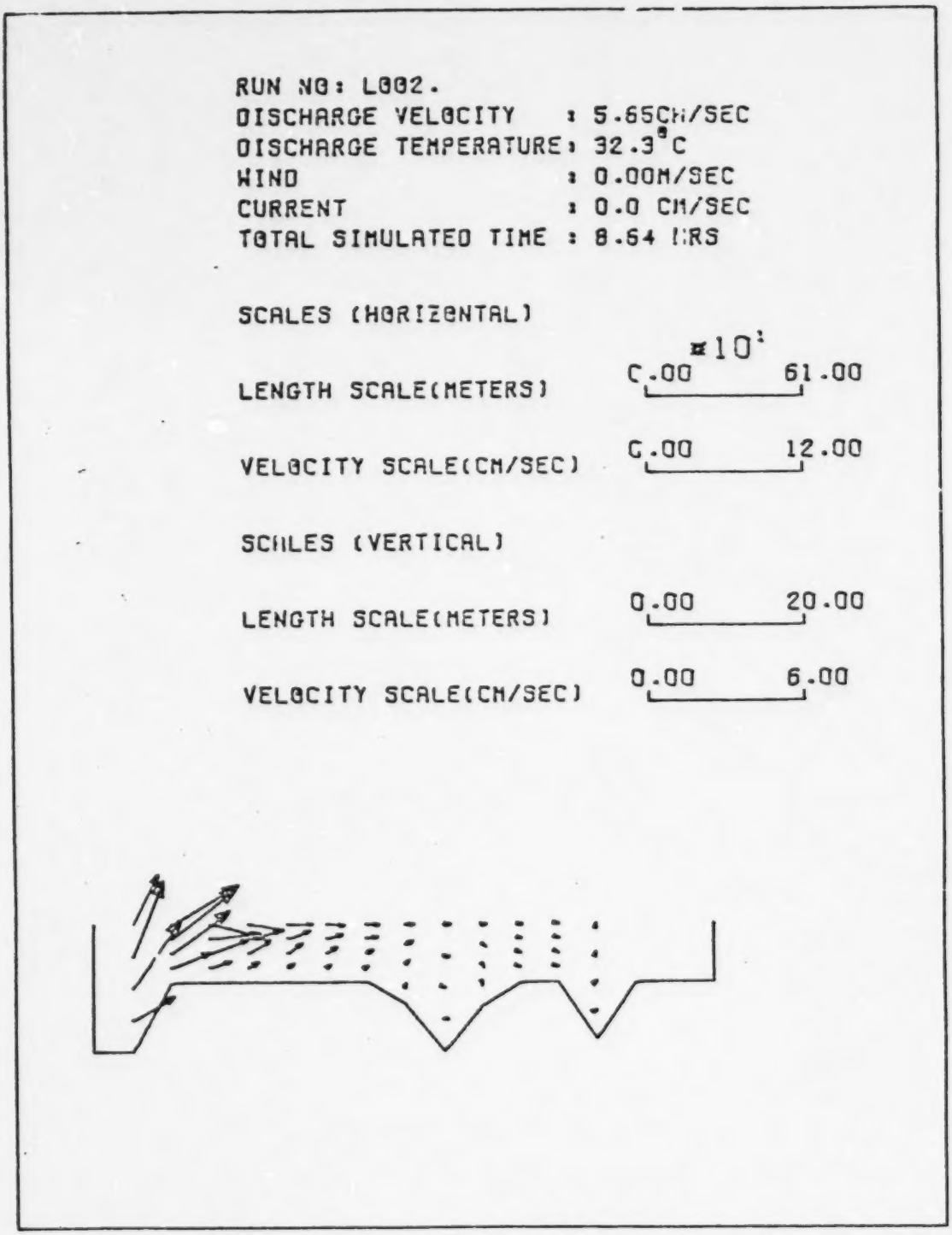


Figure 22. Velocities at I = 11, Lake Keowee (rigid-lid model)

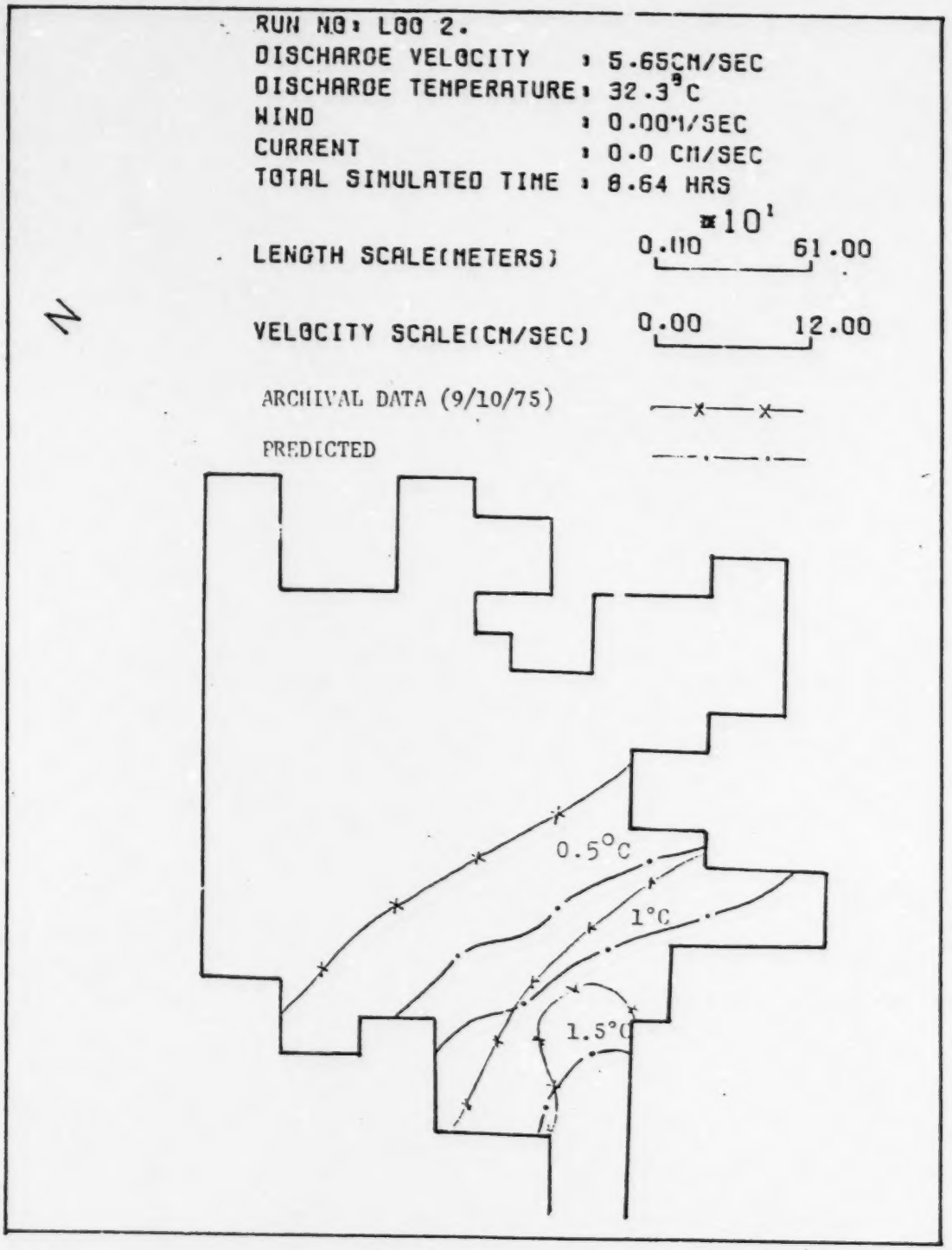


Figure 23. Isotherms: measured and predicted (temperatures above ambient)

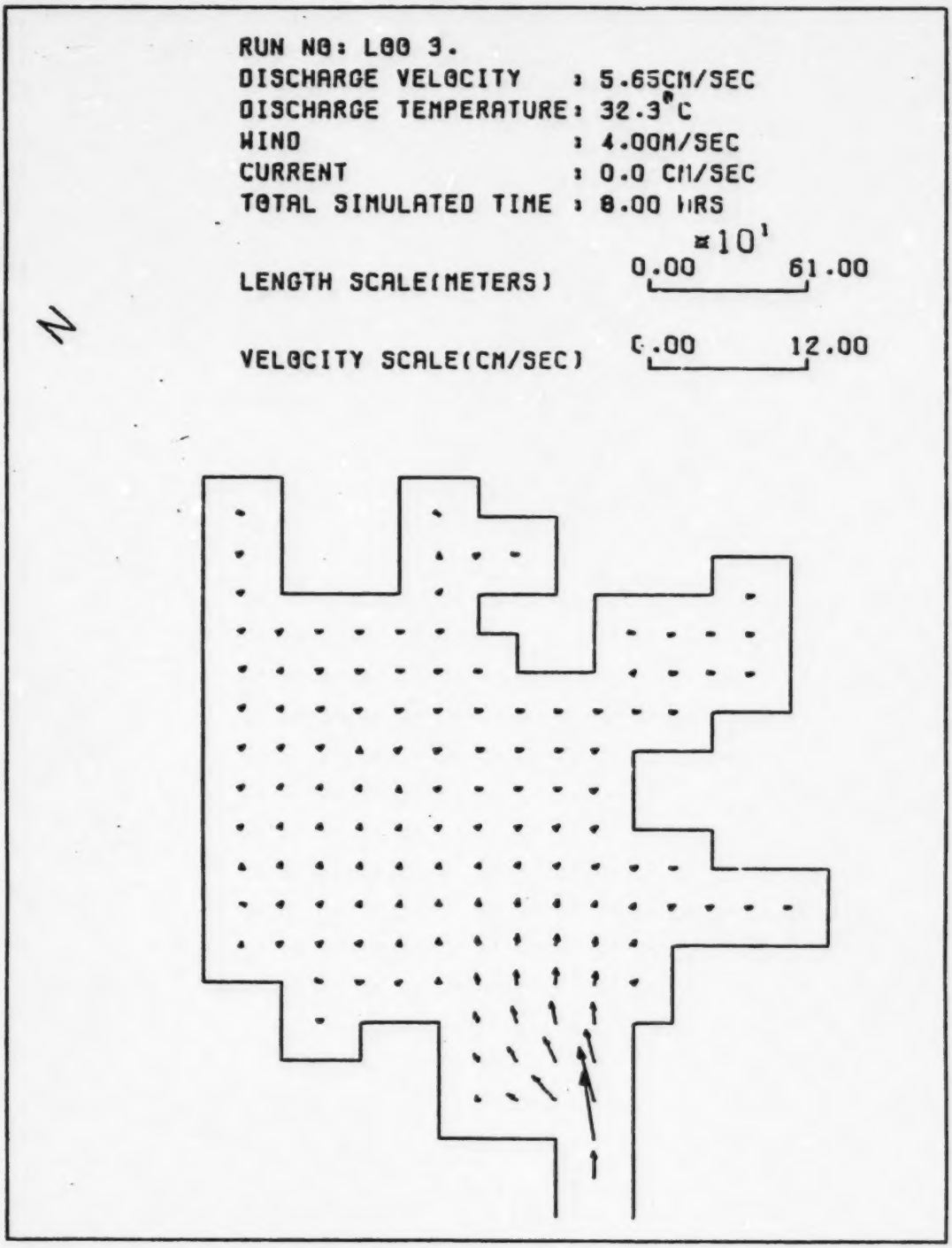


Figure 24. Velocities at K = 1, Lake Keowee (rigid-lid model)

RUN NO: L003.
DISCHARGE VELOCITY : 5.65CM/SEC
DISCHARGE TEMPERATURE: 32.3°C
WIND : 4.00M/SEC
CURRENT : 0.0 CM/SEC
TOTAL SIMULATED TIME : 4.32 HRS

SCALES (HORIZONTAL)

LENGTH SCALE(METERS) ×10¹ 0.00 61.00

VELOCITY SCALE(CM/SEC) 0.00 12.00

SCALES (VERTICAL)

LENGTH SCALE(METERS) 0.00 20.00

VELOCITY SCALE(CM/SEC) 0.00 6.00

Figure 25. Velocities at J = 7, Lake Keowee (rigid-lid model)

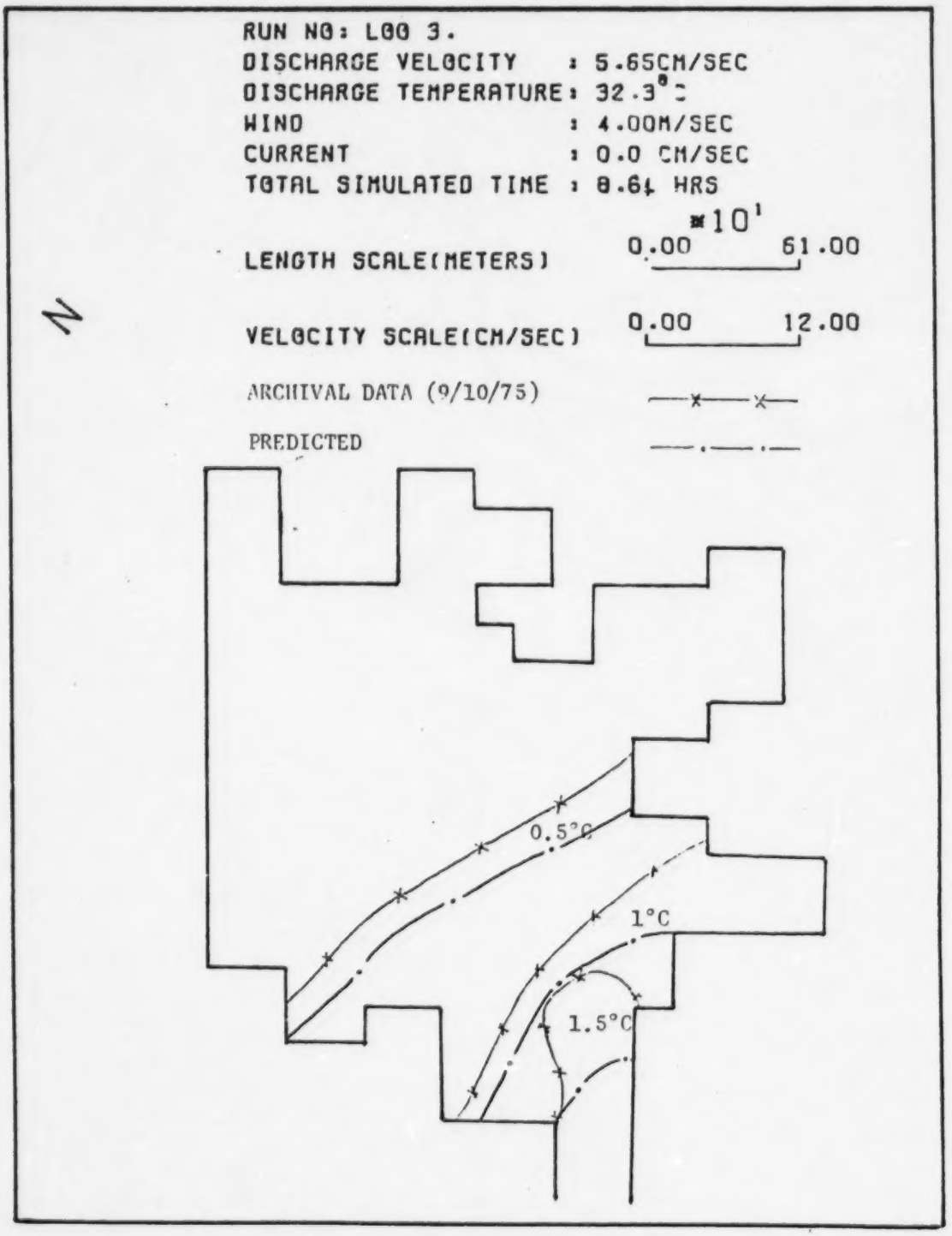


Figure 26. Isotherms: measured and predicted (temperatures above ambient)

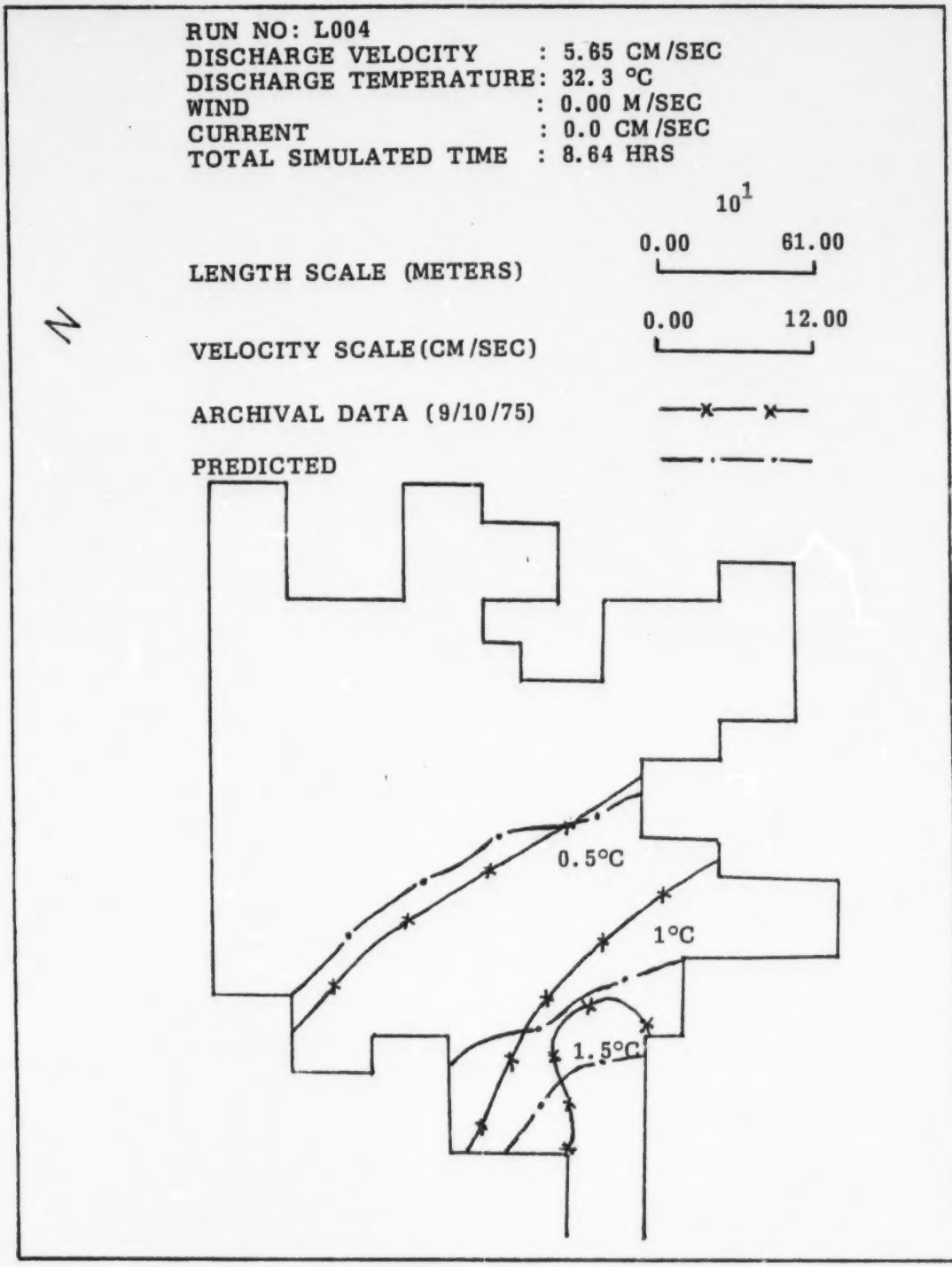


Figure 27. Isotherms: measured and predicted (temperatures above ambient)

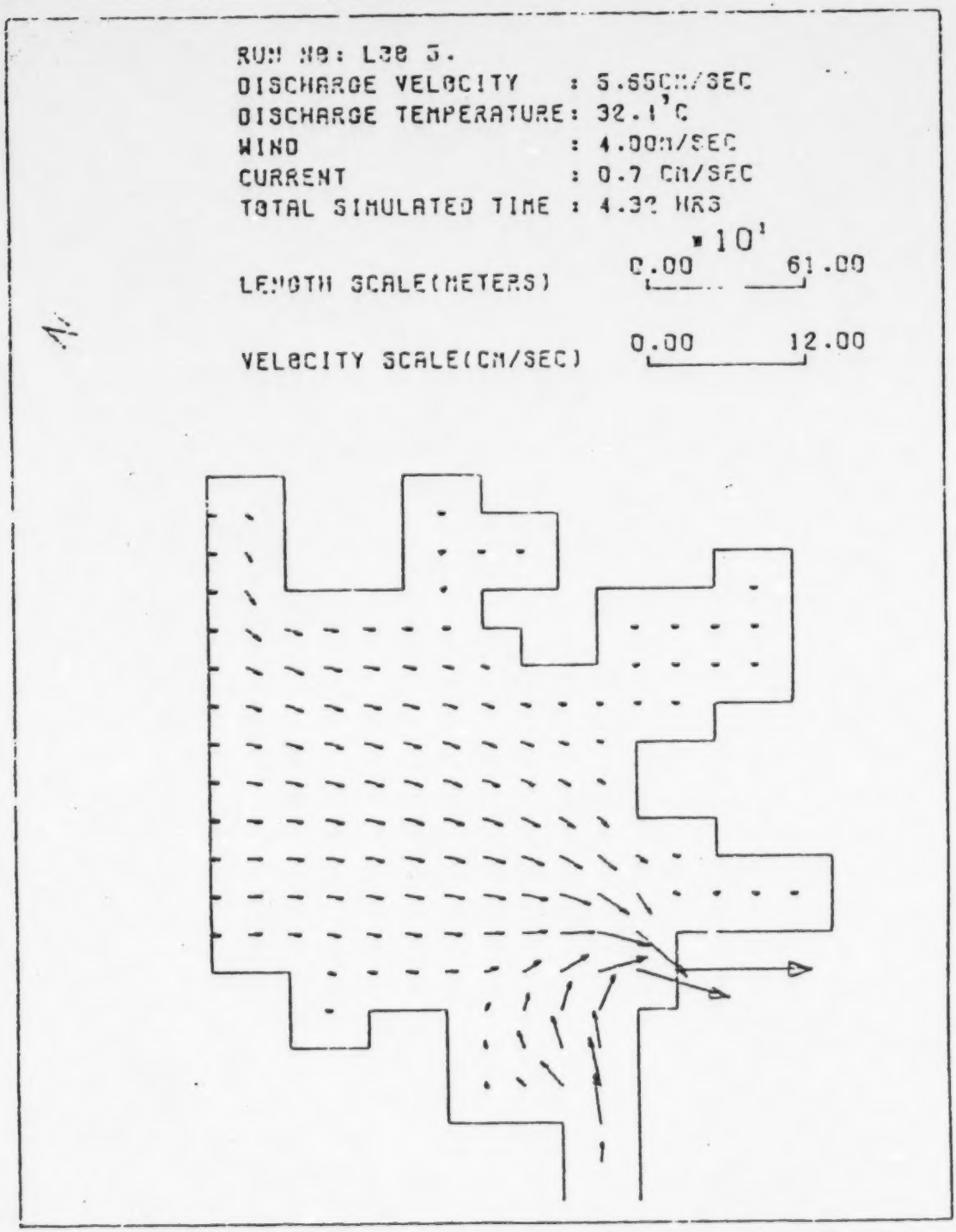


Figure 28. Velocities at K = 1, Lake Keowee (rigid-lid model)

RUN NO: 1005.
DISCHARGE VELOCITY : 5.65CM/SEC
DISCHARGE TEMPERATURE: 32.4°C
WIND : 4.00M/SEC
CURRENT : 0.7 CM/SEC
TOTAL SIMULATED TIME : 32.10HRS

SCALES (HORIZONTAL)

LENGTH SCALE(METERS) *10¹ 0.00 61.00

VELOCITY SCALE(CM/SEC) 0.00 12.00

SCALES (VERTICAL)

LENGTH SCALE(METERS) 0.00 20.00

VELOCITY SCALE(CM/SEC) 0.00 6.00

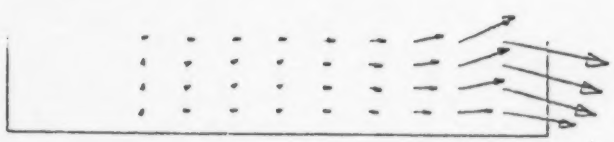


Figure 29. Velocities at J = 7, Lake Keowee (rigid-lid model)

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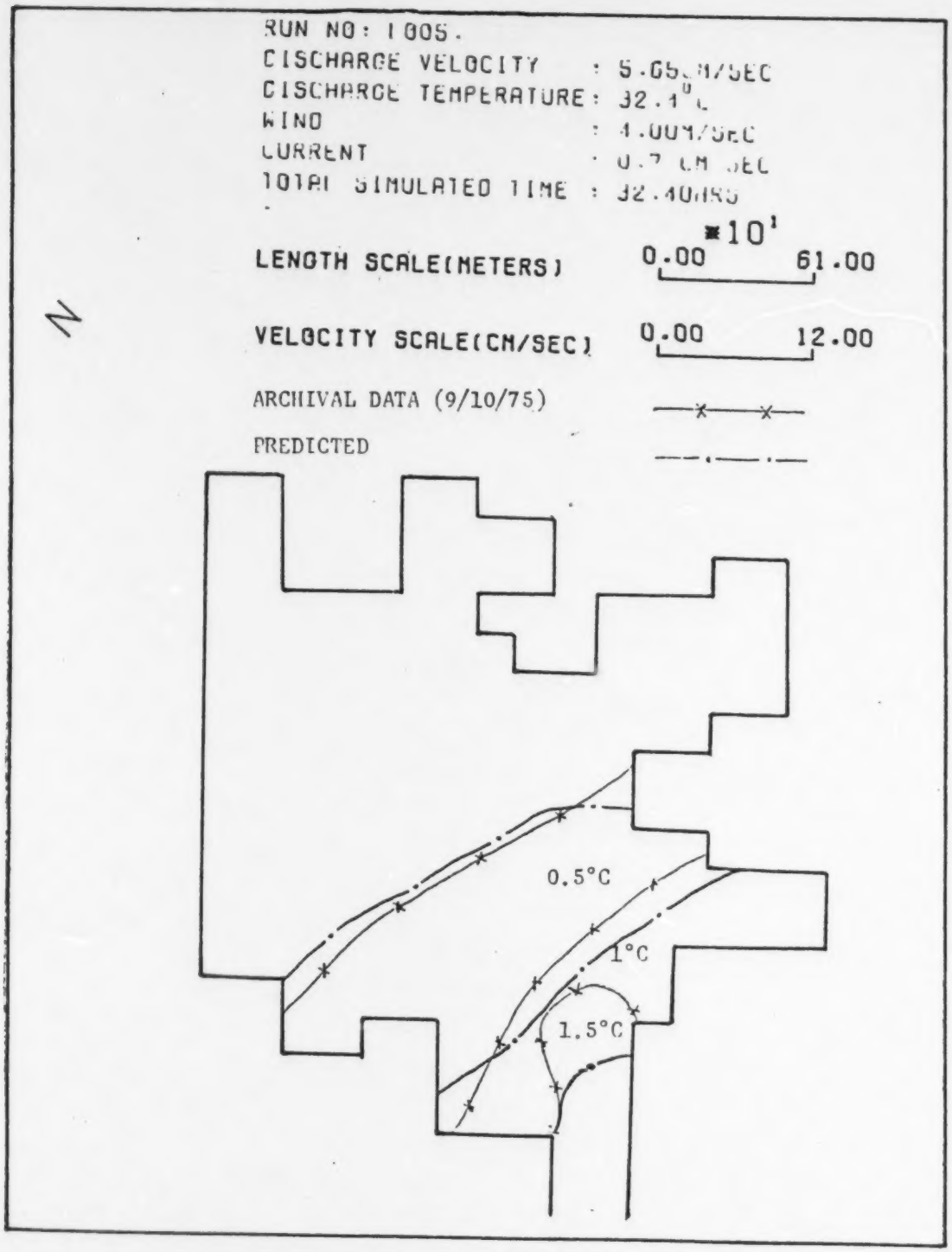

Figure 30. Isotherms: measured and predicted (temperatures above ambient)

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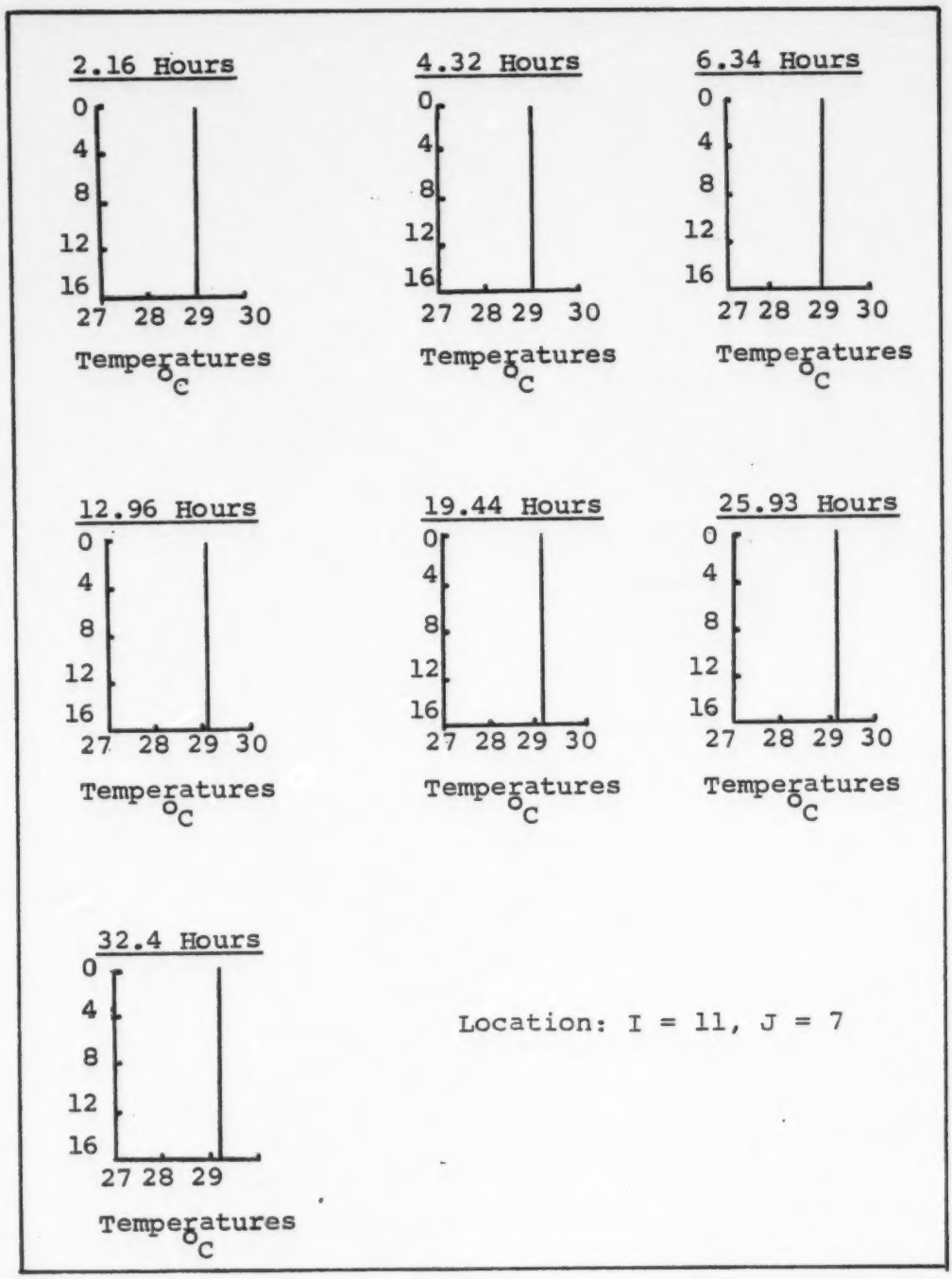

Figure 31. L005, temperature profiles

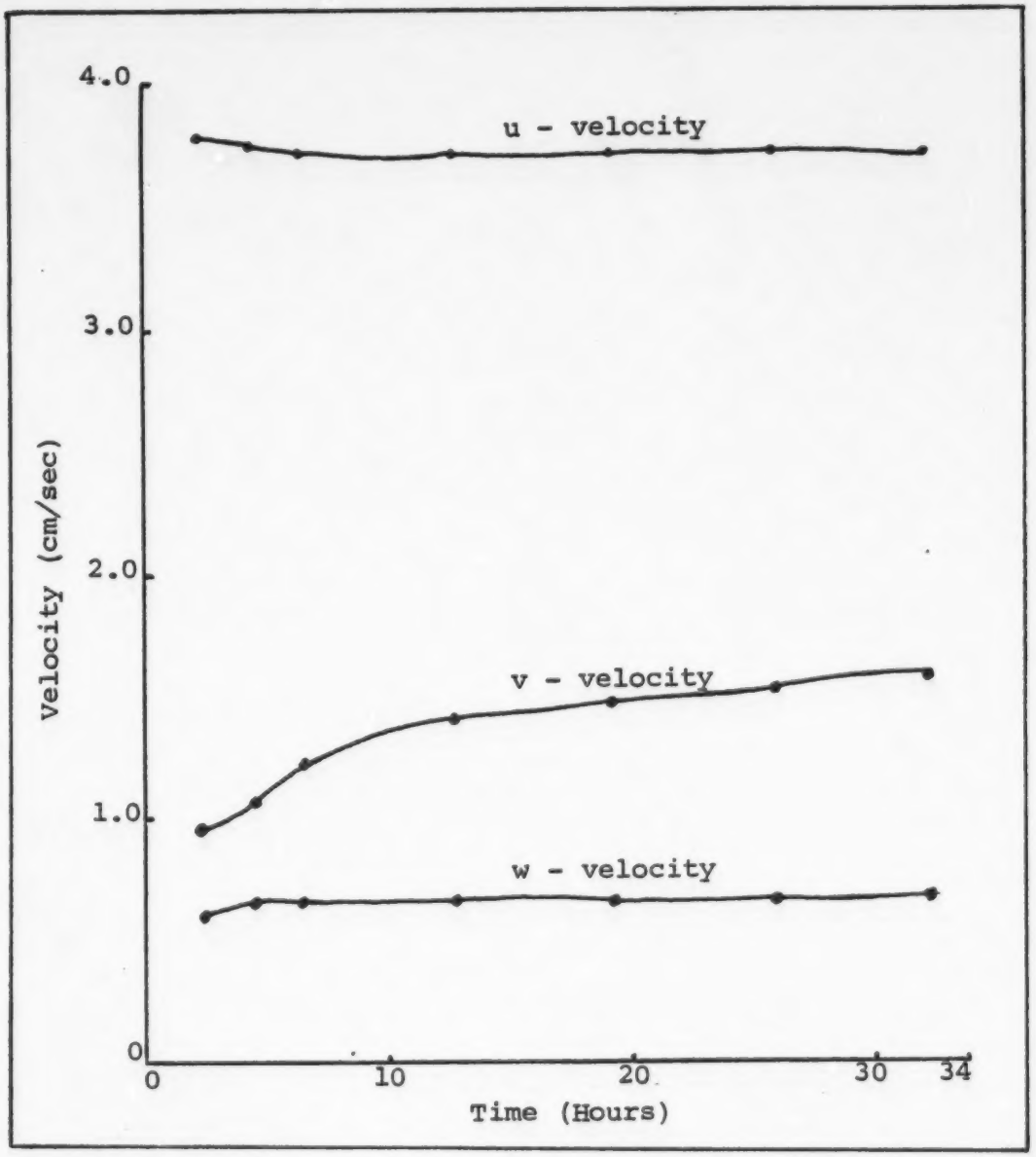

Figure 32. L005, velocity vs. time, I = 11, J = 7, K = 1

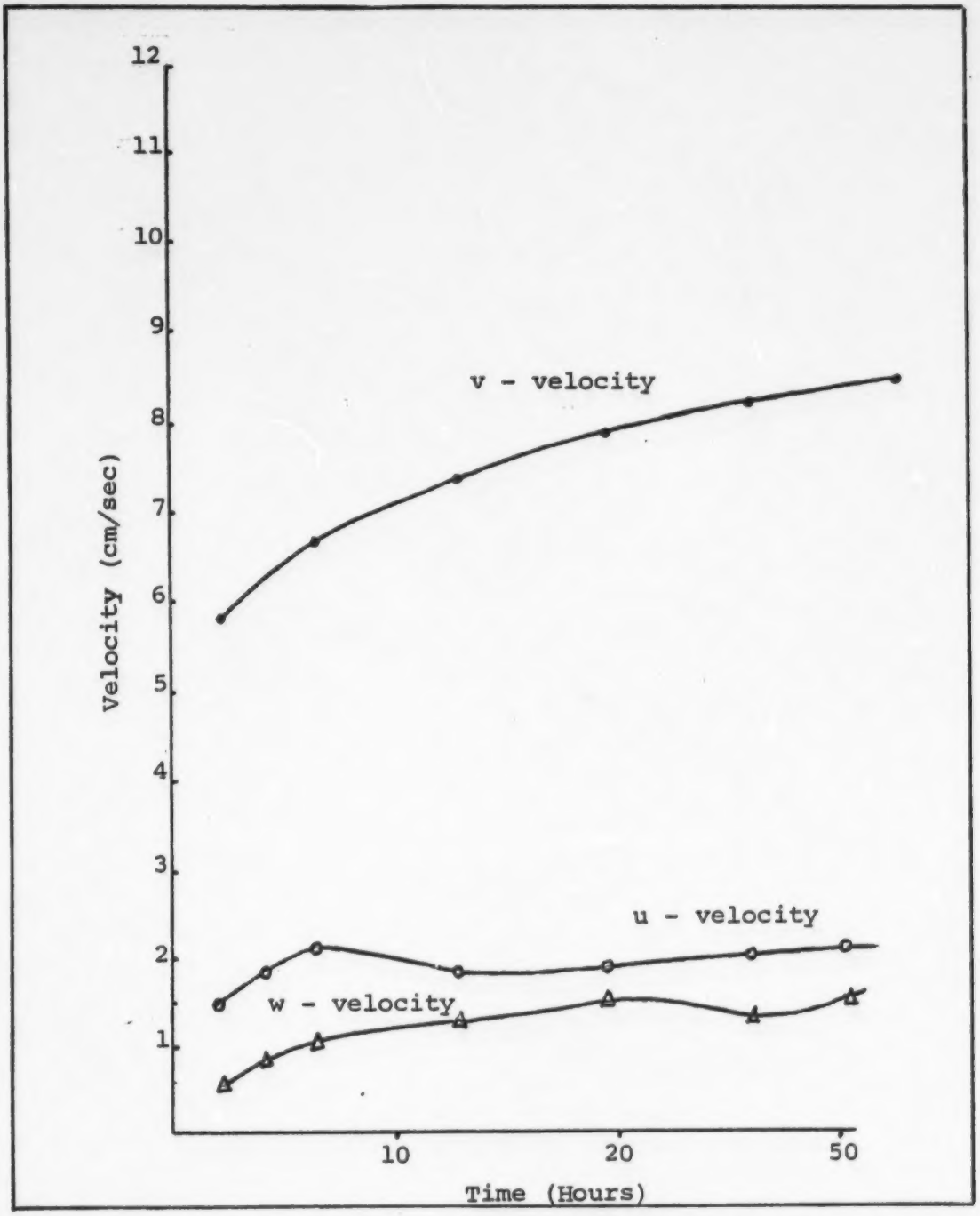

Figure 33. L005, velocity vs. time, I = 11, J = 2, K = 1

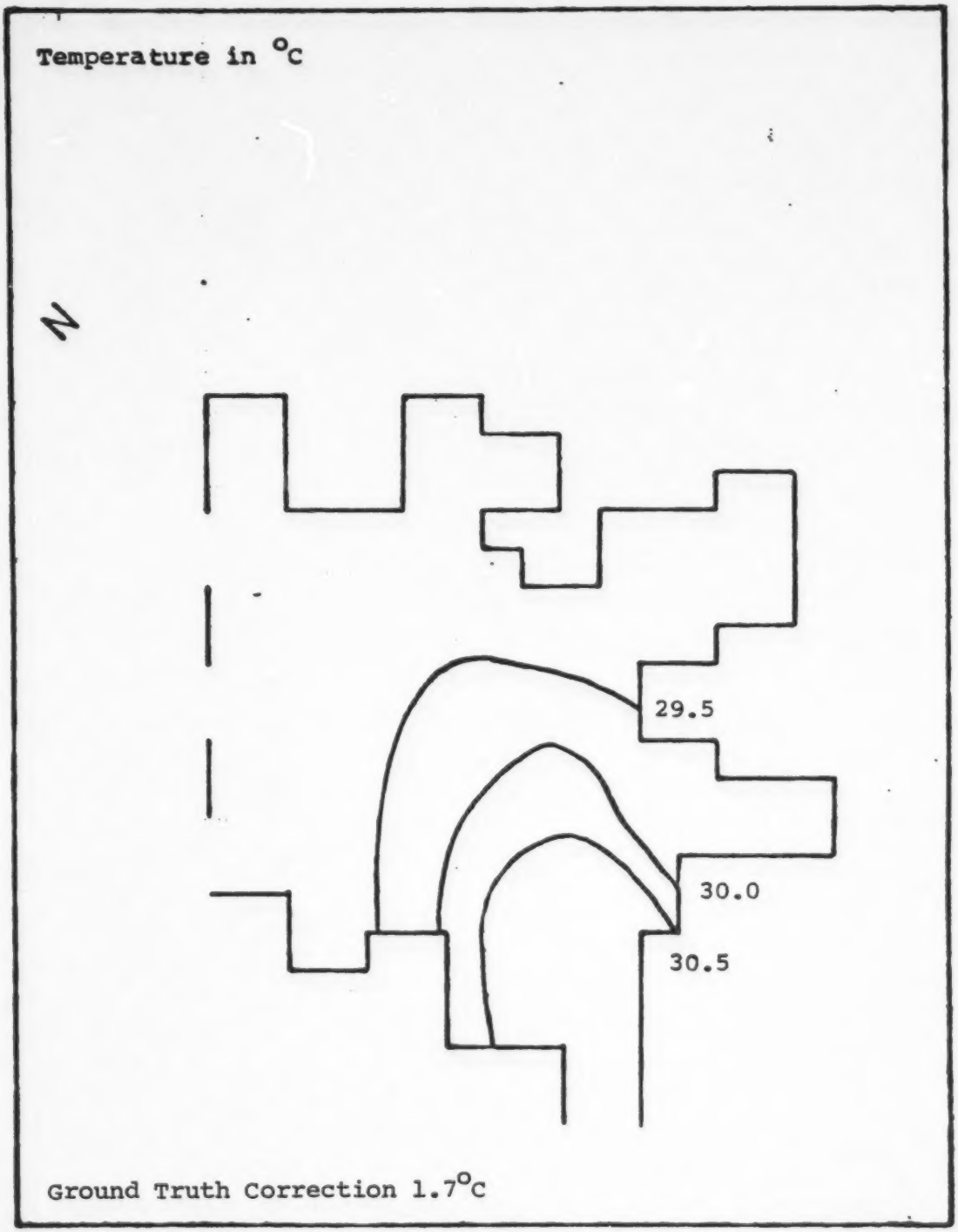

Figure 34. IR data coreesponding to 1002 hrs, August 24, 1978, Lake Keowee

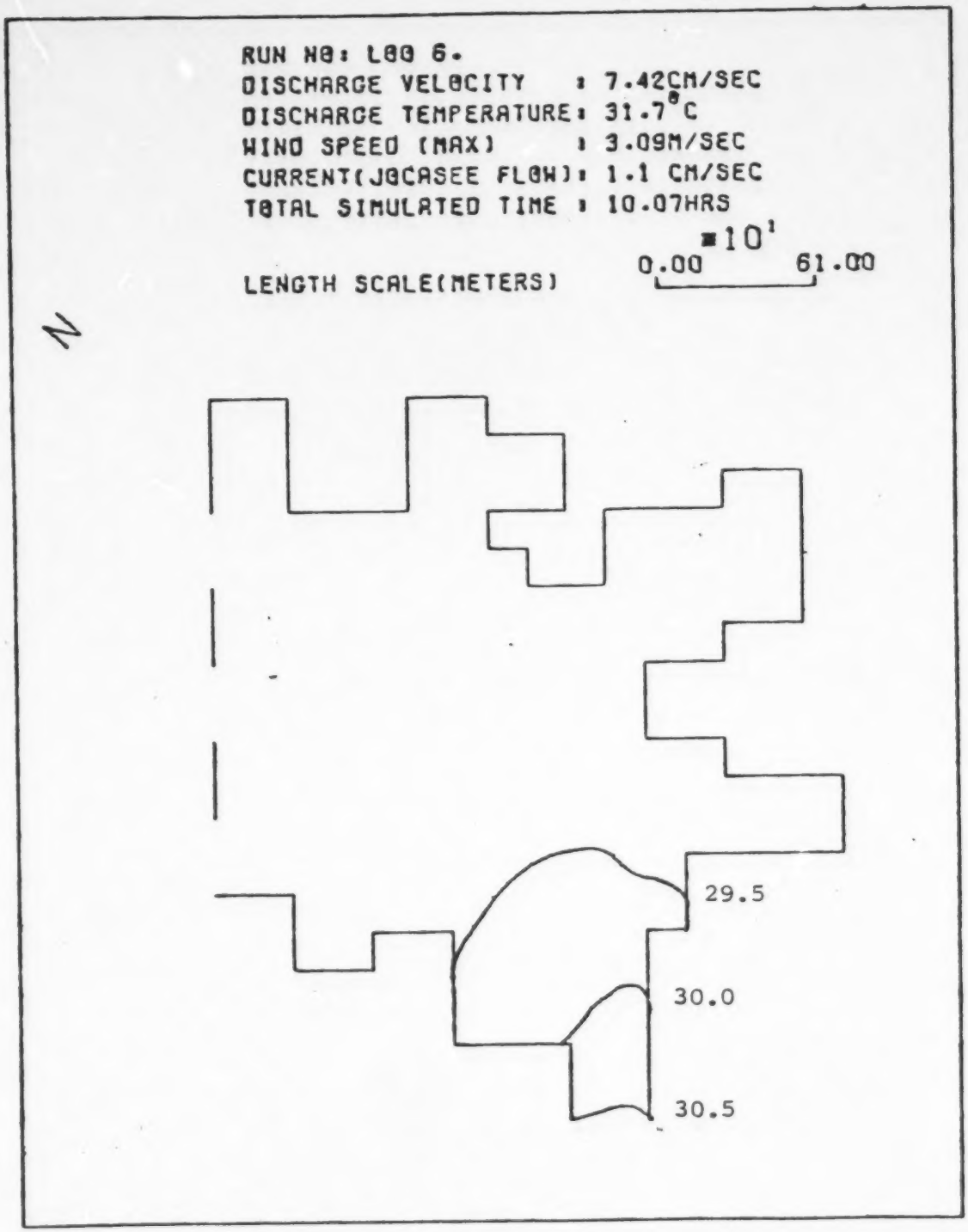

Figure 35. Isotherms at K = 1, Lake Keowee (rigid-lid model), simulations for August 24, 1978

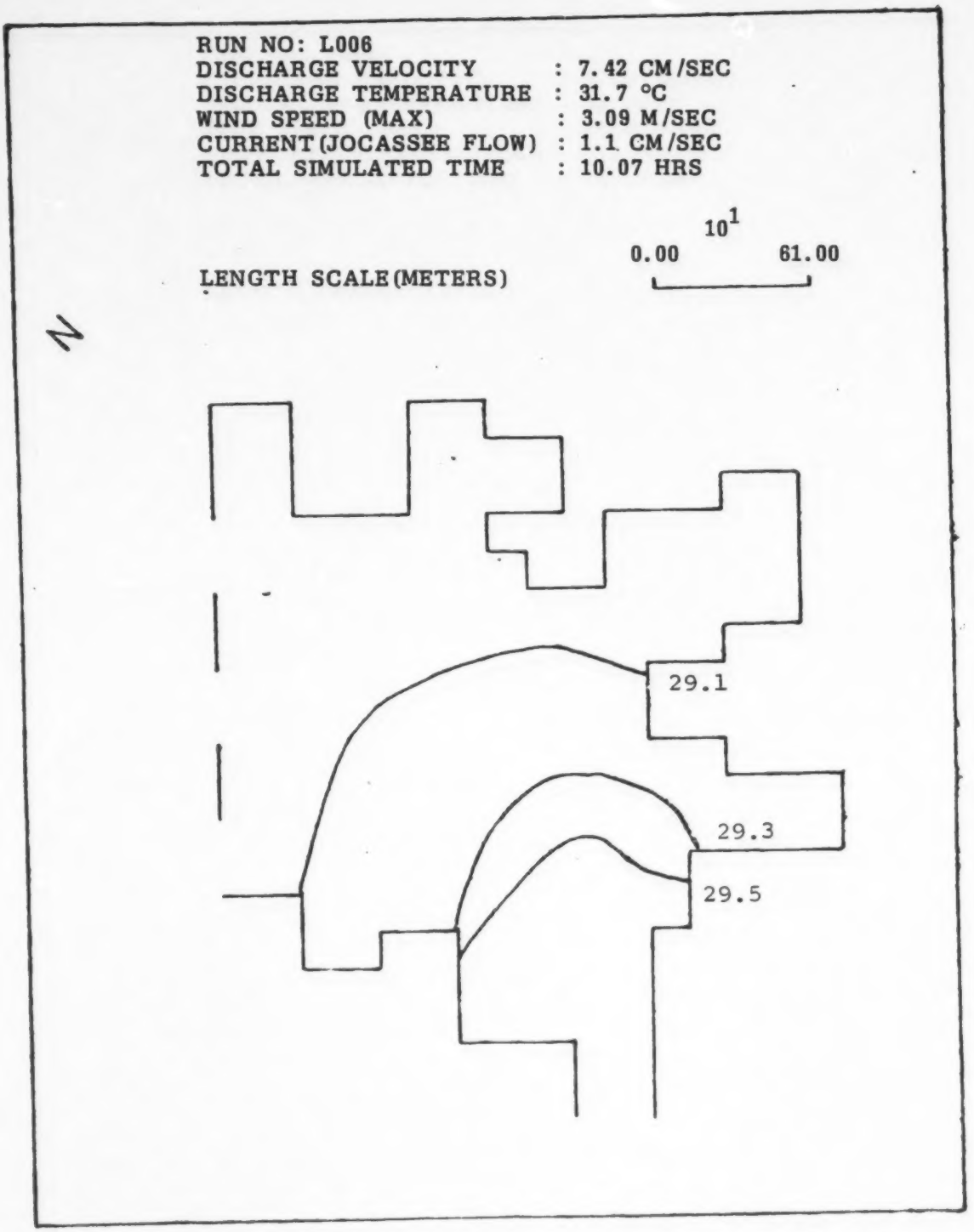

Figure 36. Isotherms at K = 1, Lake Keowee (rigid-lid model), simulations for August 24, 1978

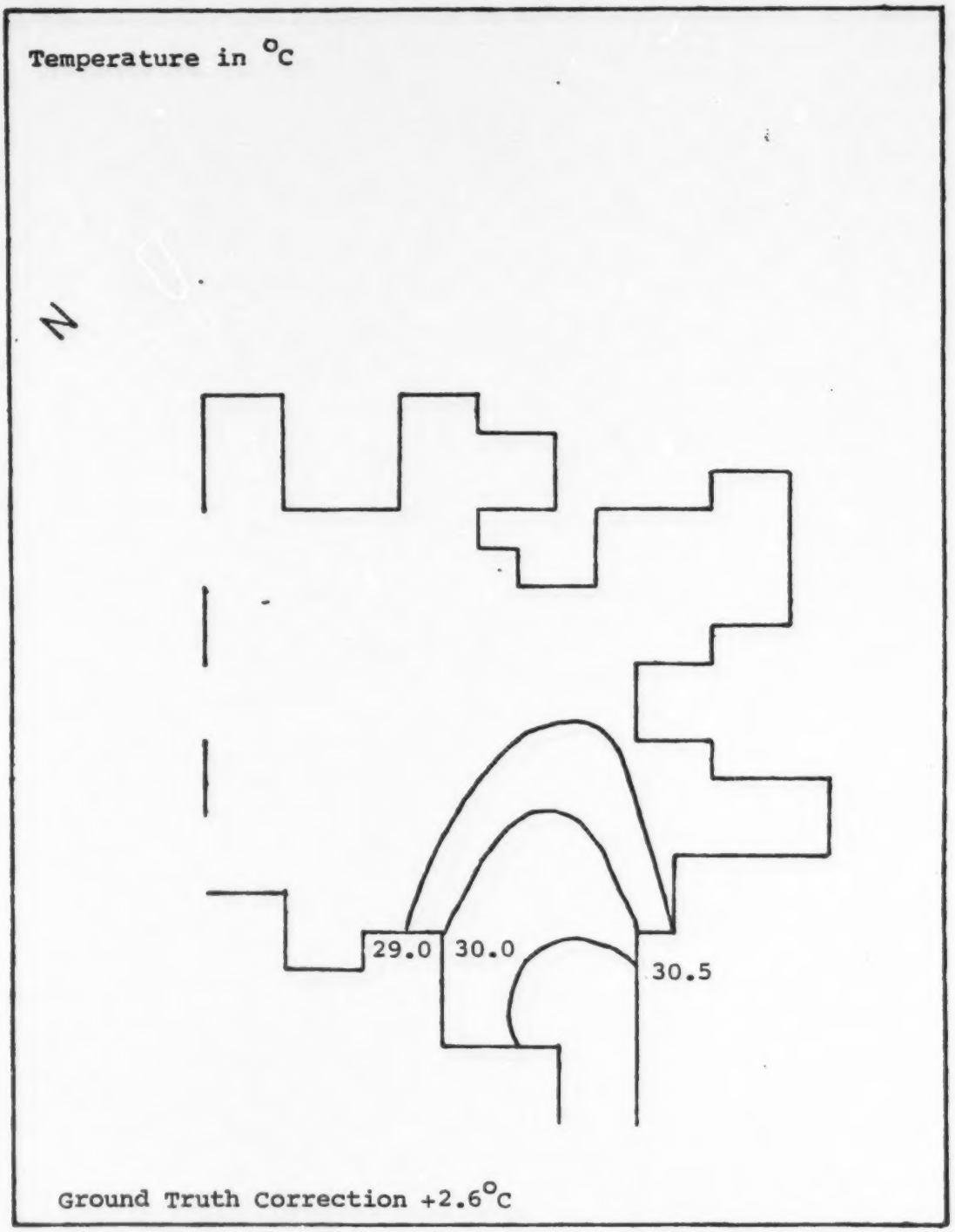

Figure 37. IR data corresponding to 0903-0953 hrs, August 25, 1978 Lake Keowee

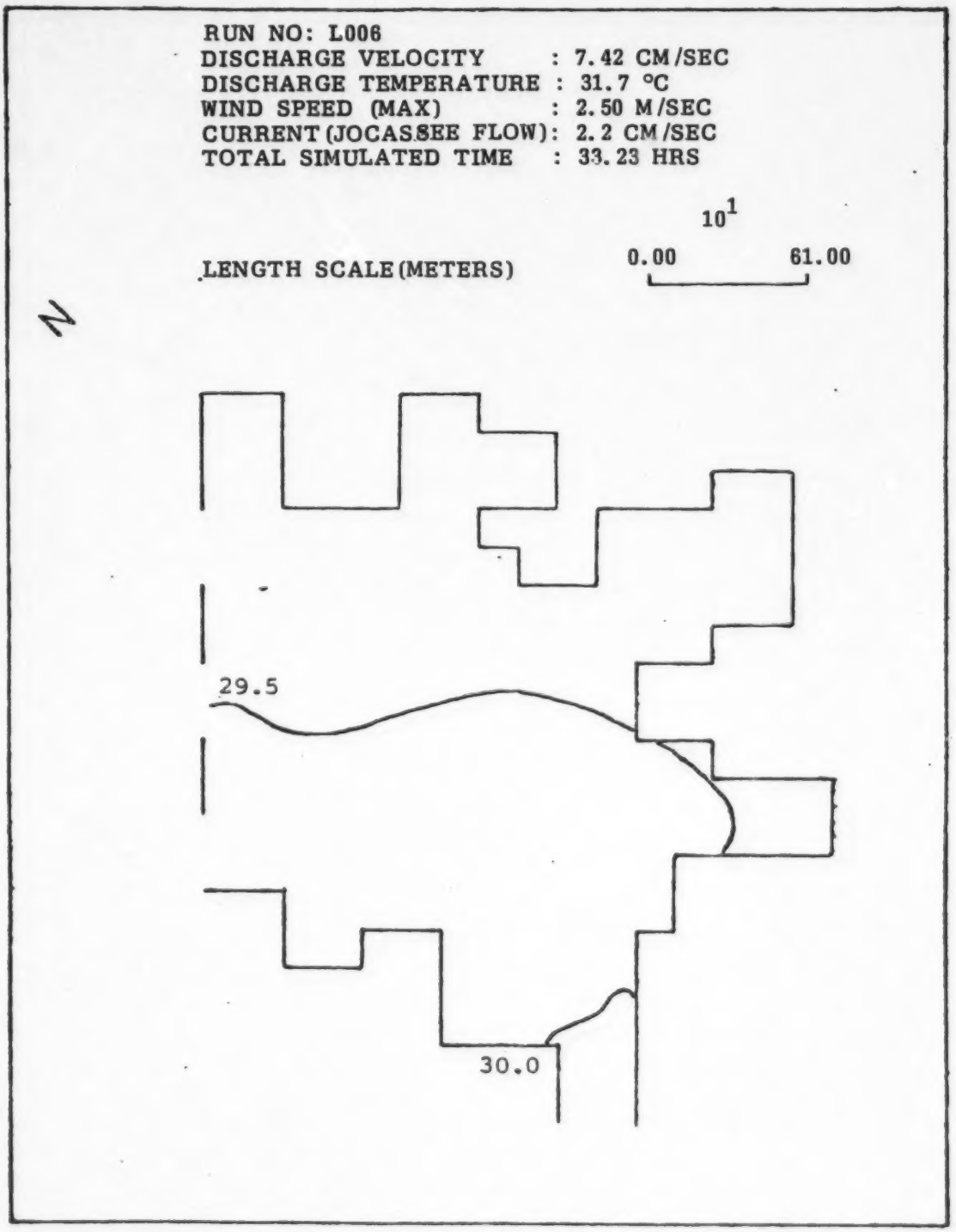

Figure 38. Isotherms at K = 1, Lake Keowee (rigid-lid model), simulations for August 25, 1978

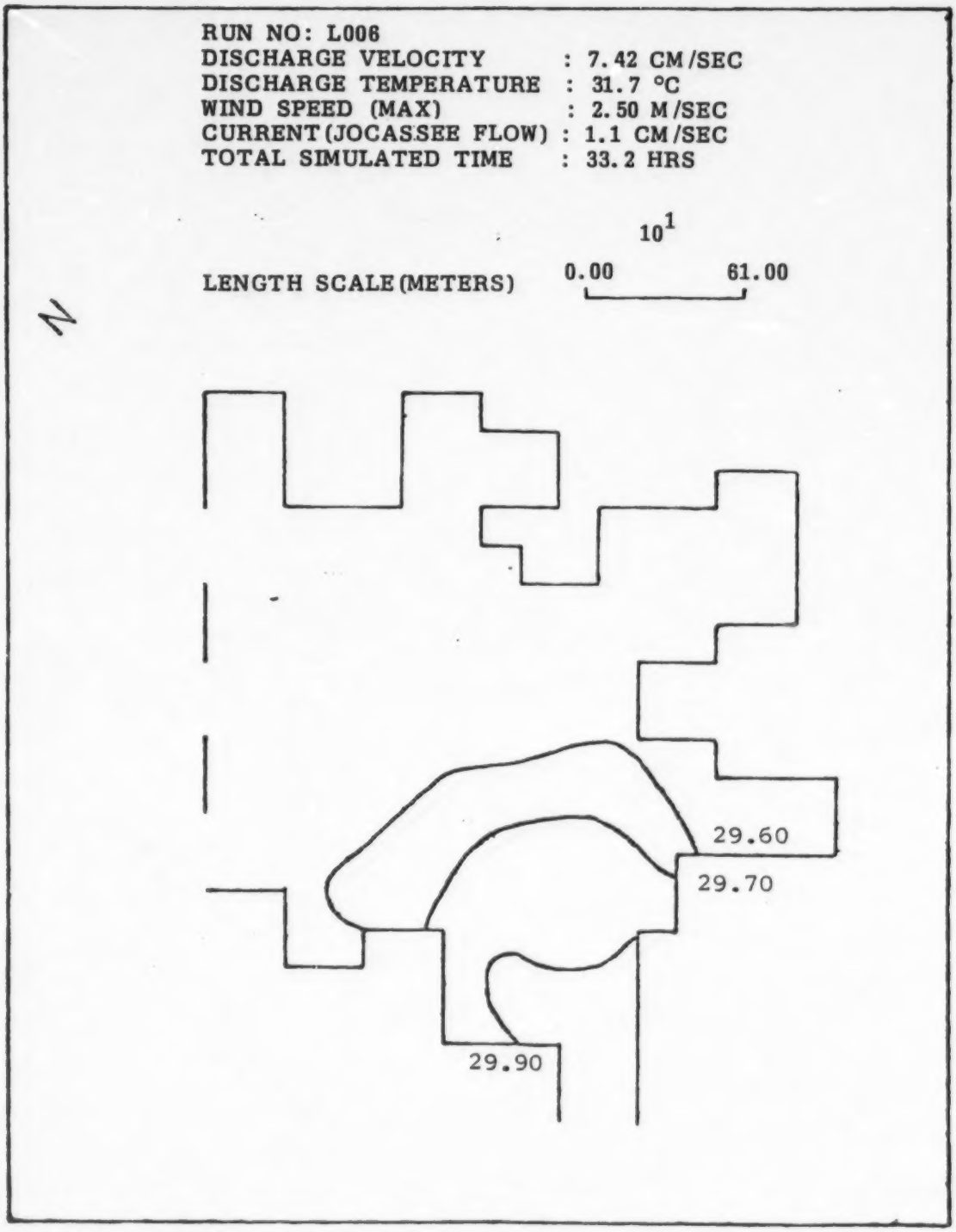

Figure 39. Isotherms at K = 1, Lake Keowee (rigid-lid model), simulations for August 25, 1978

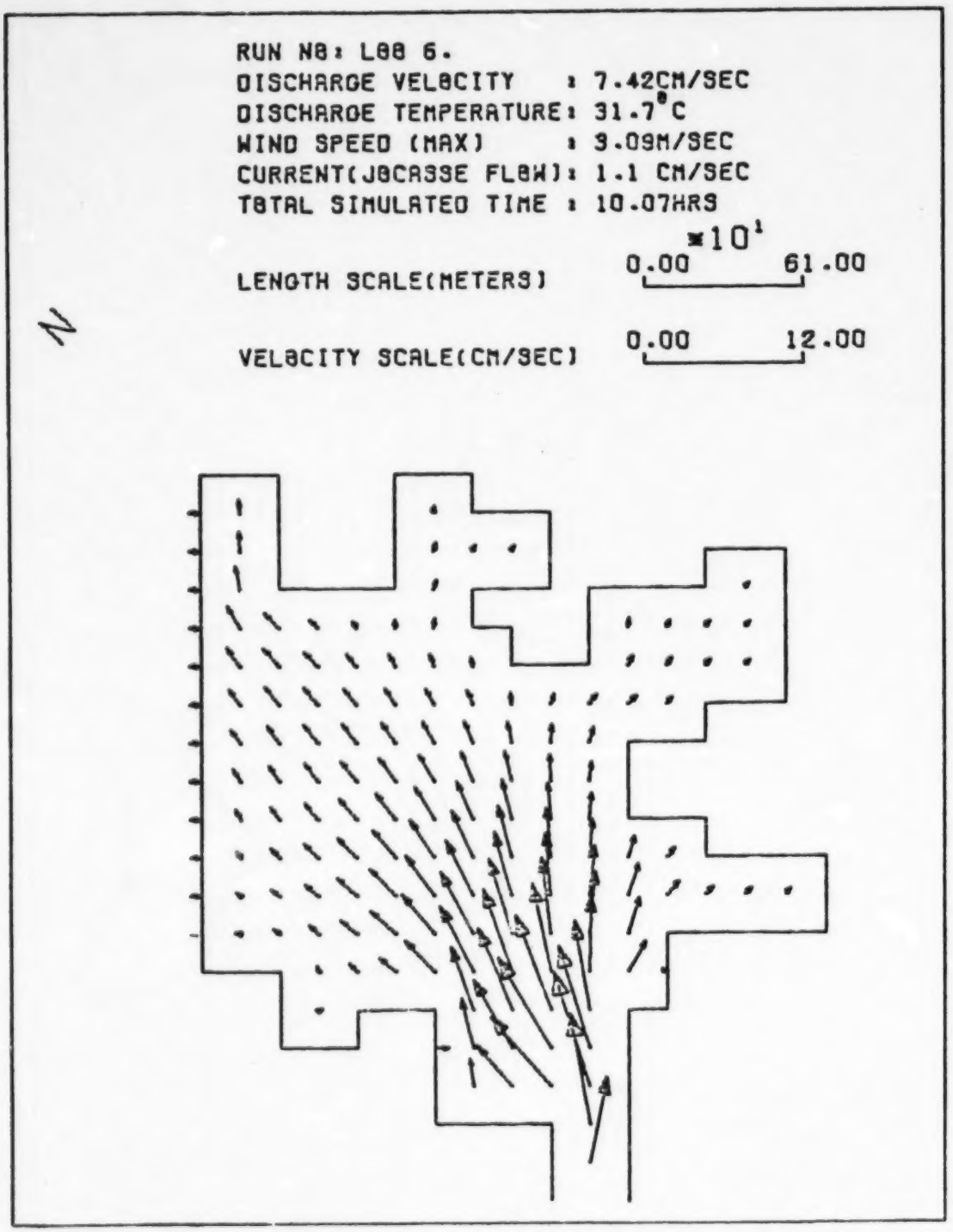

Figure 40. Velocities at K = 1, Lake Keowee (rigid-lid model), simulations for August 24, 1978

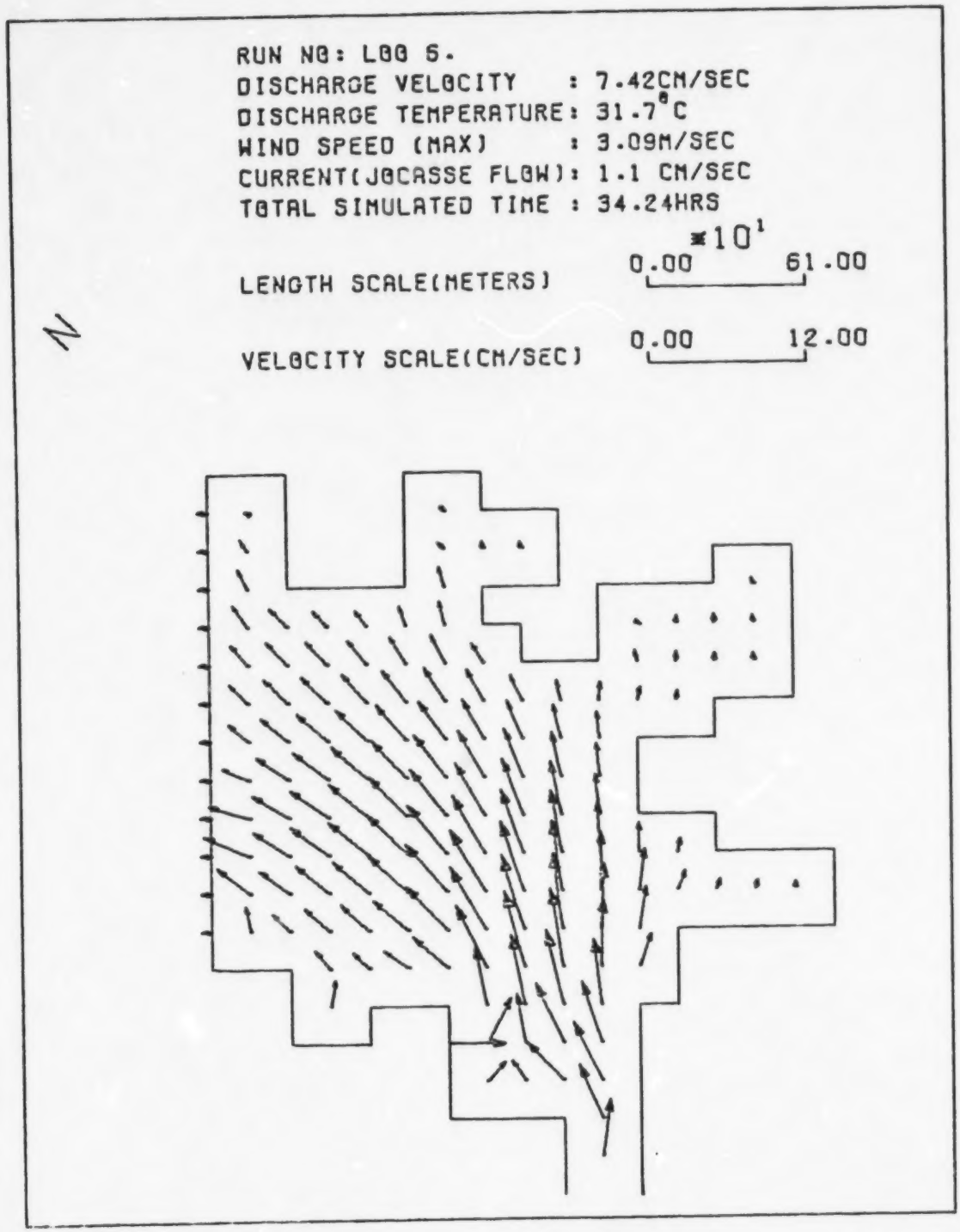

Figure 41. Velocities at K = 1, Lake Keowee (rigid-lid model), simulations for August 25, 1978

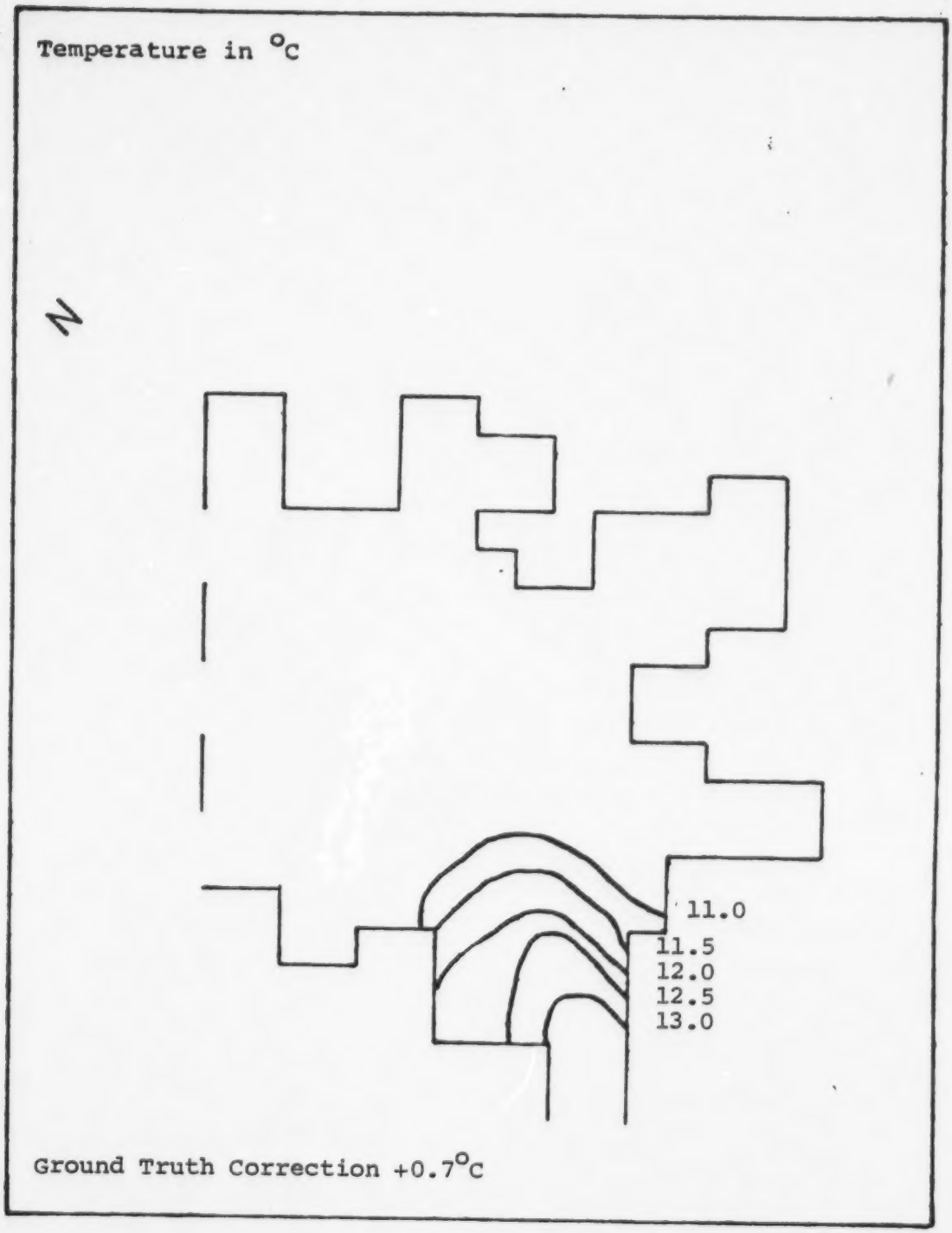

Figure 42. IR data corresponding to 1648-1651 hrs, February 27, 1979, Lake Keowee

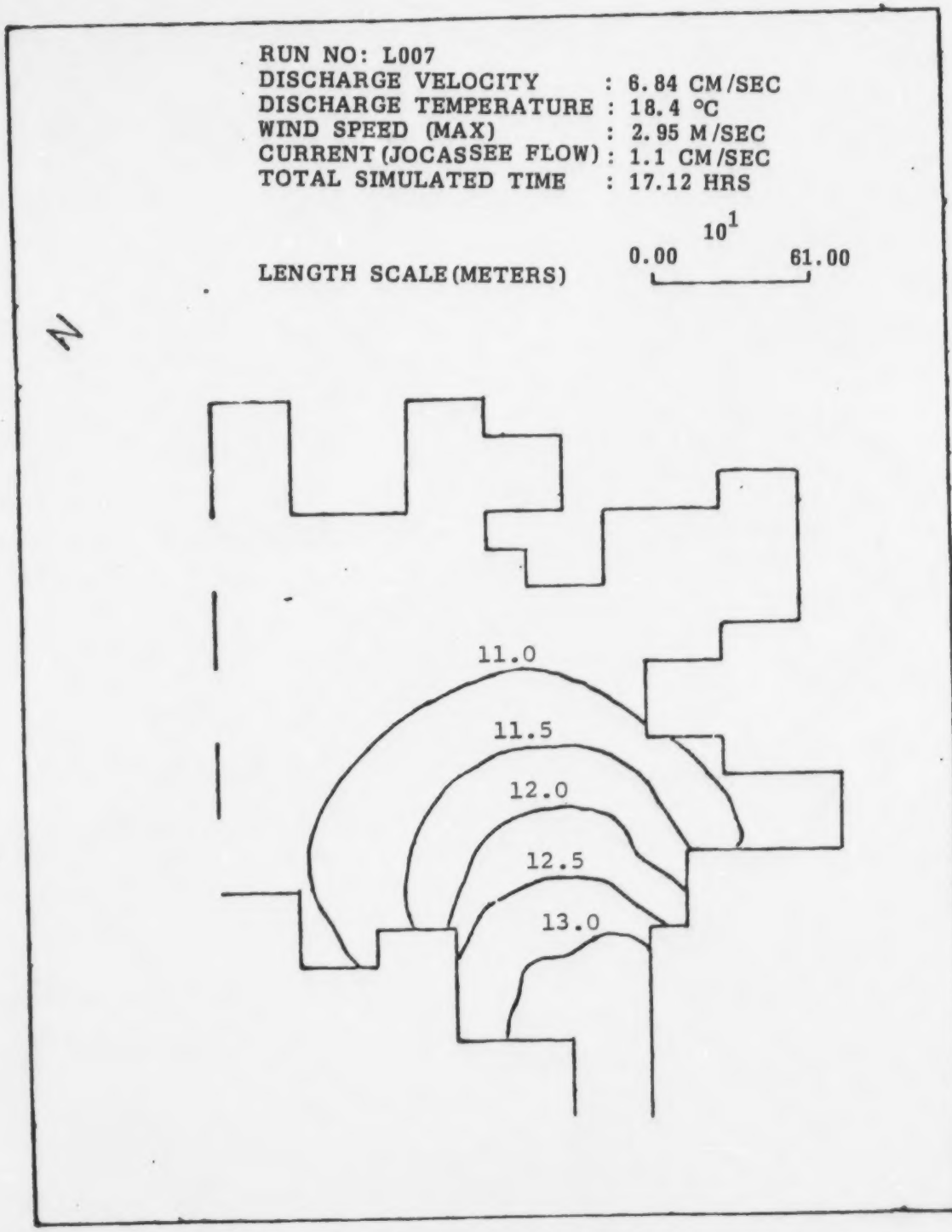

Figure 43. Isotherms at K = 1, Lake Keowee (rigid-lid model), simulations for February 27, 1979

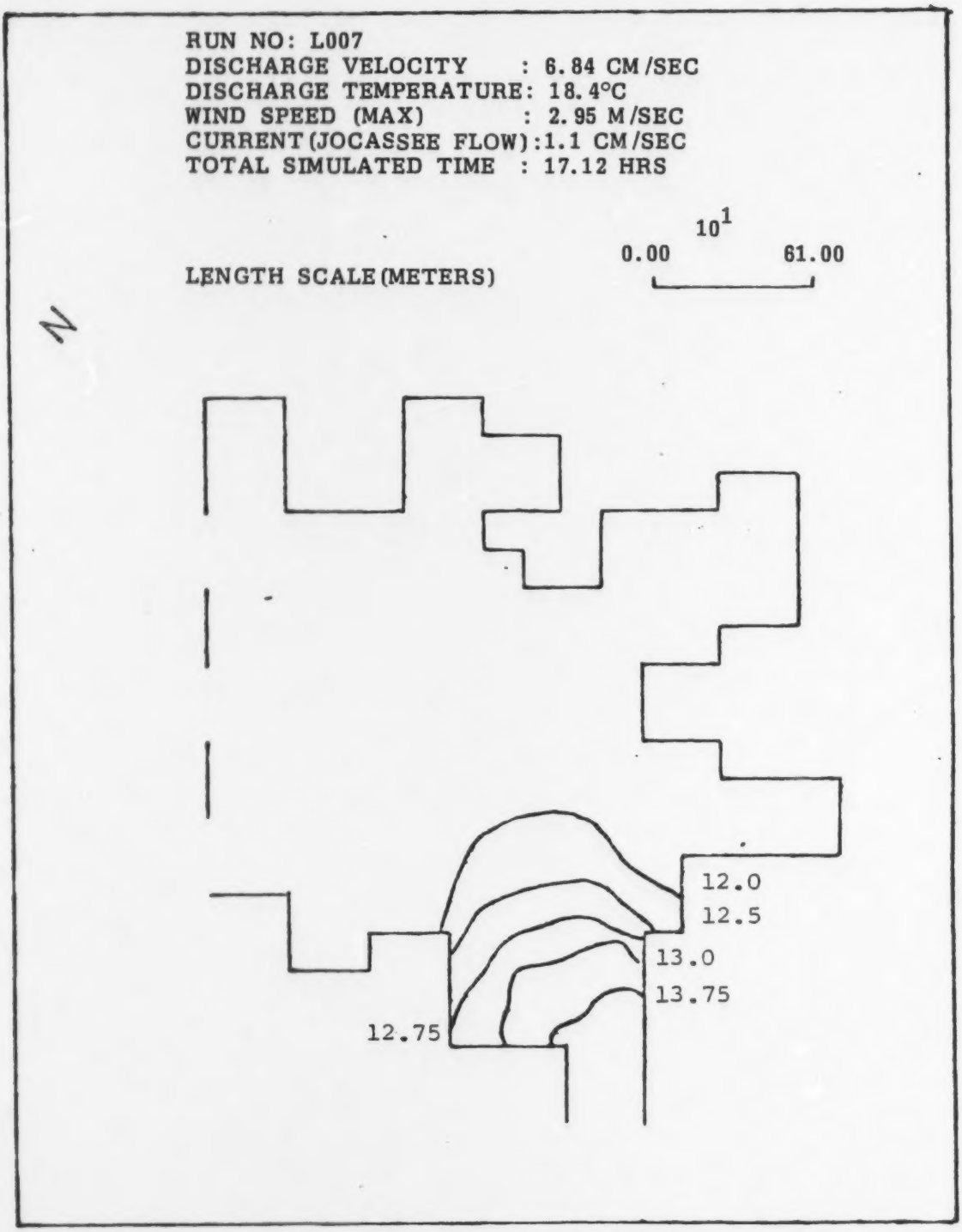

Figure 44. Isotherms at K = 1, Lake Keowee (rigid-lid model) simulations for February 27, 1979

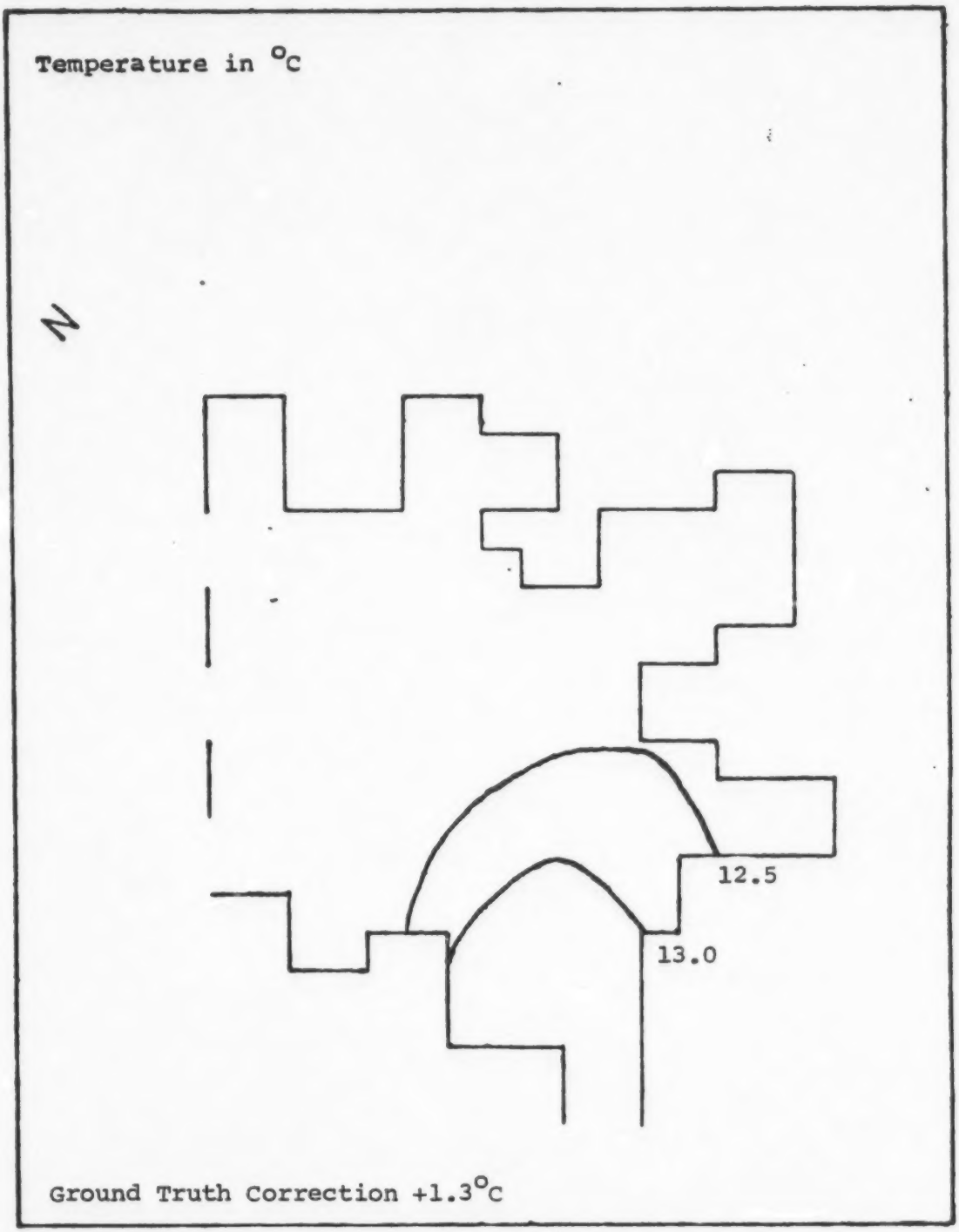

Figure 45. IR data corresponding to 0948-0957 hrs, February 28, 1979 Lake Keowee

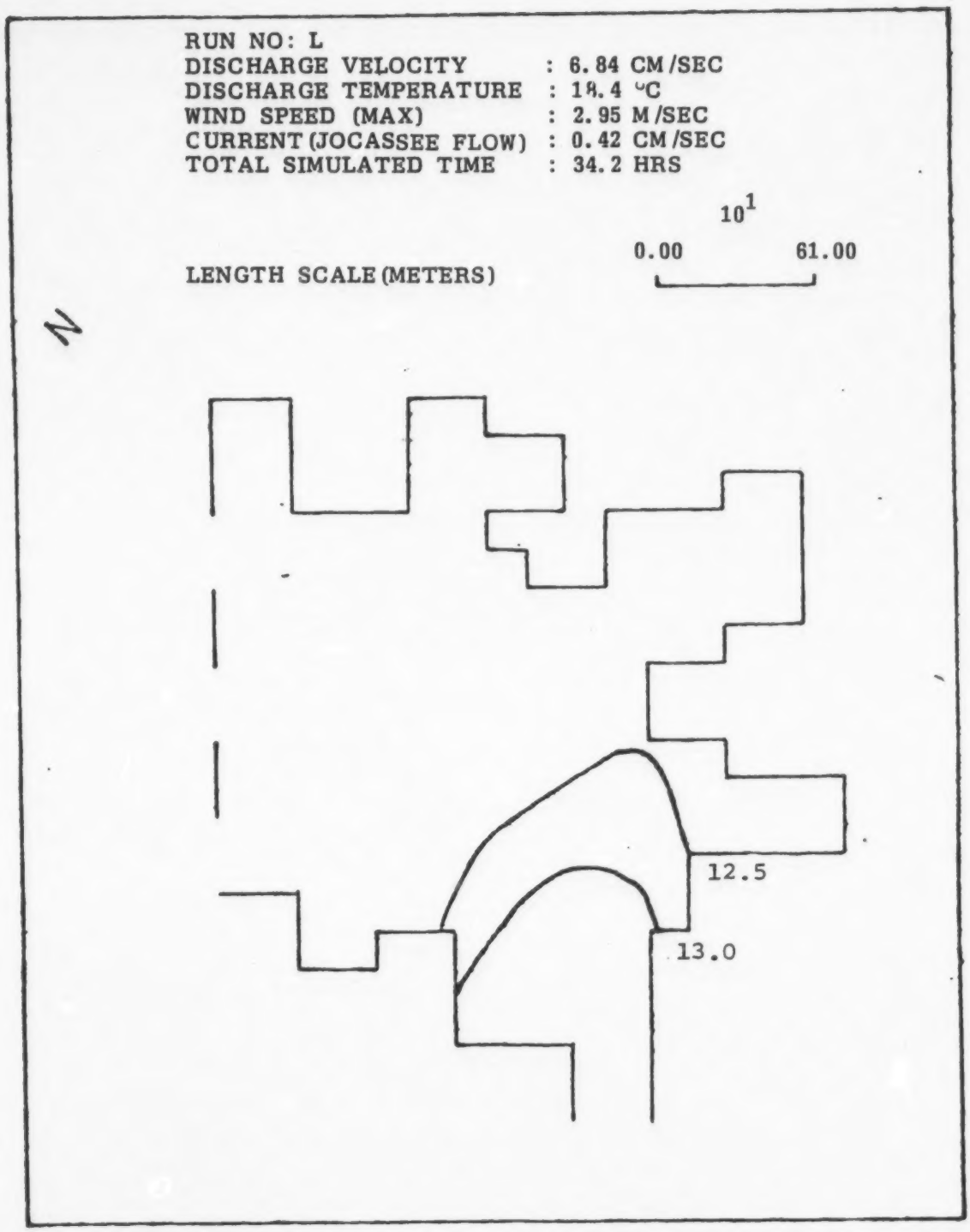

Figure 46. Isotherms at K = 1, Lake Keowee (rigid-lid model), simulations for February 28, 1979

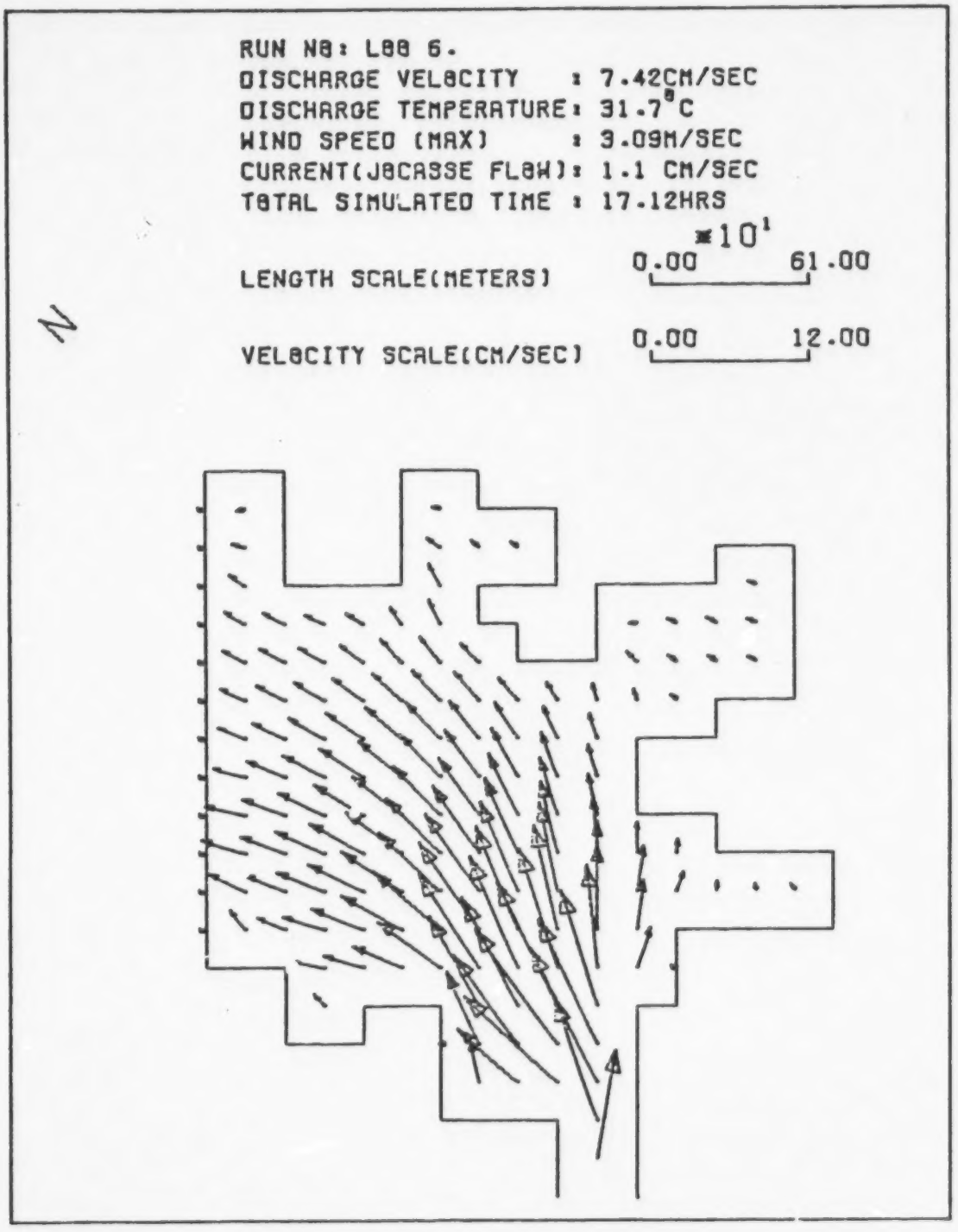

Figure 47. Velocities at K = 1, Lake Keowee (rigid-lid model), simulations for February 27, 1979

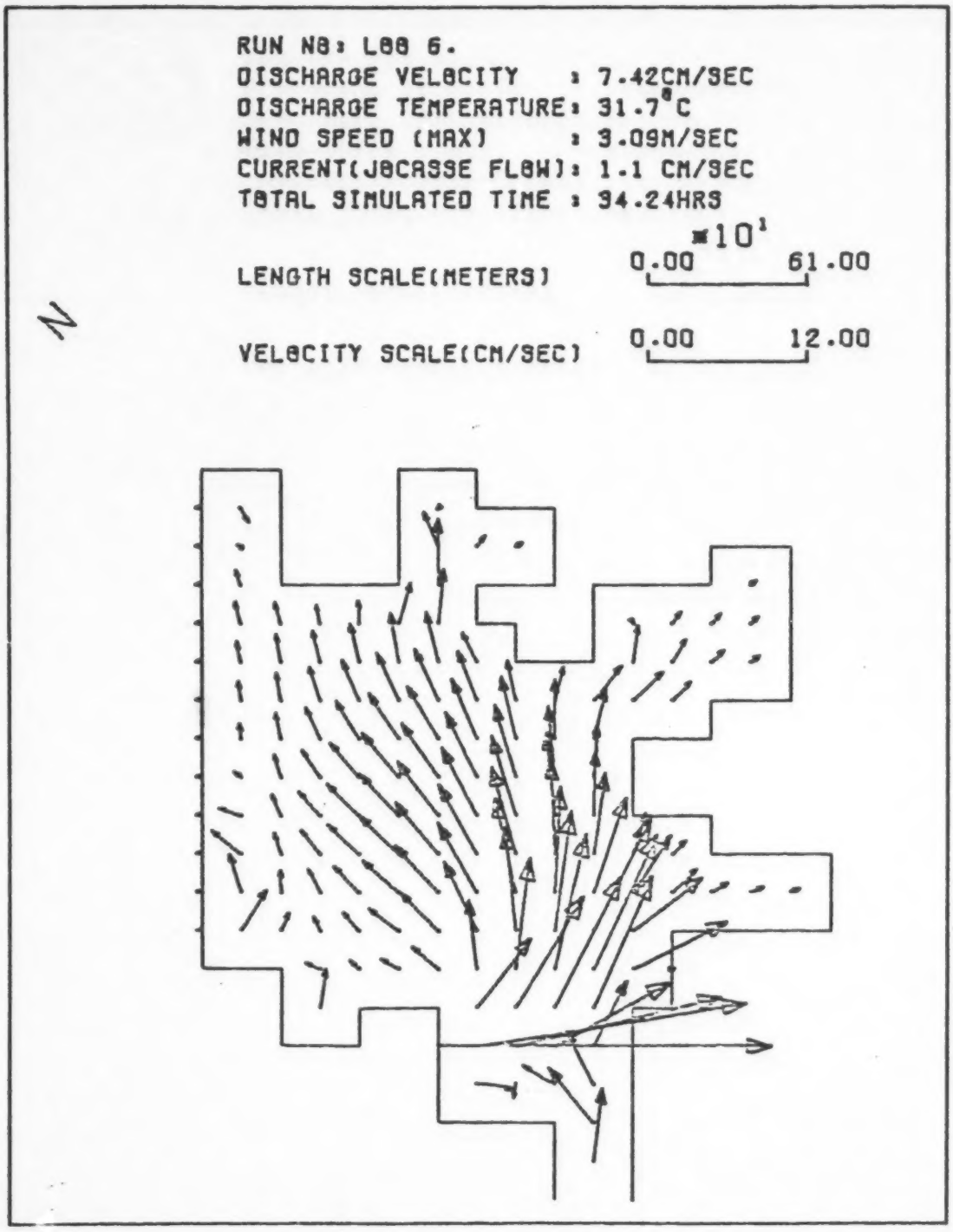

Figure 48. Velocities at K = 1, Lake Keowee (rigid-lide model), simulations for February 28, 1979

Table 1. Monthly Gross Thermal Capacity Factors (Percent) for Oconee Nuclear Station

MONTH	1973	1974	1975	1976	1977
Jan.	0	13	37	30	90
Feb.	0	28	22	49	77
Mar.	0	29	57	47	72
Apr.	0	26	61	27	92
May	4	5	76	33	76
Jun.	9	43	78	64	46
Jul.	15	38	80	59	44
Aug.	15	31	82	90	36
Sep.	16	46	76	77	
Oct.	23	19	75	61	
Nov.	23	31	92	52	
Dec.	27	30	92	55	
Annual Average	11	28	69	59	

Data based on three-unit capability for entire period.

$$\text{Gross Thermal Capacity Factor for ONS (\%)} = \frac{\text{Actual MWH(t)} \times 100}{\text{7704 MW(t)} \times \text{Hours in Period}}$$

Table 2. Operating Conditions of Oconee Nuclear Power Plant at Lake Keowee (September 10, 1975)

Flow Rate : 7087 m/min

Inlet Temperature : 26.6 °C

Outlet Temperature : 32.4 °C

The hourly averages of wind, air temperature and relative humidity:

Time	Wind Speed (MPH)	Wind Direction (°N)	Air Temp.	Relative Humidity
9:00	7.7	15	69.0	100
10:00	6.8	65	74.0	70
11:00	8.3	80	77.0	60
12:00	7.2	95	77.0	63
13:00	9.7	115	78.0	66
14:00	11.3	205	79.0	64
15:00	-	-	77.0	66
16:00	10.2	75	73.0	84

Table 3. Input Data for the 3-D Model (Lake Keowee)

Flow Rate:	118.12 m^3/sec
Inlet Temperature:	25.6 °C
Discharge Temperature:	32.4 °C
Discharge Velocity:	5.65 cm/sec
Ambient Temperature:	28.9 °C
Depth at Discharge:	30 meters
Discharge Width:	152.4 meters
Air Temperature:	26.11 °C
Wind Speed:	12.83 ft/sec
Vertical Eddy Diffusivity:	86.1 cm^2/sec
Horizontal Eddy Diffusivity:	9.2×10^{-3}/sec

Table 4. Volume and Area Data for Lake Keowee

WATER SURFACE ELEVATION (m)	(ft.)	SURFACE AREA (SQ. KM.)	STORAGE VOLUME (10^9 m^3)
246.9	810	83.3	1.42
245.4	805	78.8	1.30
* 243.8	800	74.4	1.18
242.3	795	70.1	1.07
240.8	790	65.8	0.97
239.3	785	61.2	0.87
237.7	780	56.6	0.78
237.1	778	55.1	0.75
** 236.2	775	52.8	0.70
234.7	770	48.9	0.62
231.6	760	41.5	0.48
228.6	750	35.3	0.36
225.6	740	27.8	0.27
222.5	730	22.5	0.19
219.4	720	17.8	0.13
216.4	710	13.2	0.08
213.4	700	9.6	0.05
210.3	690	5.7	0.02
207.3	680	3.1	0.01
204.2	670	1.3	0.004
201.2	660	0.6	0.001
198.1	650	0.3	-----

* Full Pond

** Maximum Allowable Drawdown

Table 5. Inflows and Outflows to Lake Keowee, August 24, 1978

TIME Aug. 24 1978	OCONEE DISCHARGE (m^3/min)	OCONEE DISCHARGE TEMP. °C	NET JOCASSEE FLOW (CFS)	KEOWEE HYDRO FLOW (CFS)
12.00 AM	8172.9	31.8	-2638	6636
01.00	8177.5	31.8	-6059	6696
02.00	8178.6	31.9	-7982	5416
03.00	8180.1	32.1	-12036	5416
04.00	8185.4	32.3	-12066	6756
05.00	8179.4	32.4	-11985	2276
06.00	8181.7	32.5	-10598	48
07.00	8313.0	32.3	-5970	48
08.00	8183.5	32.4	-995	48
09.00	8176.4	32.5	100	48
10.00	8183.9	32.5	100	48
11.00	8177.1	32.5	100	48
12.00 PM	8159.9	32.6	100	48
1.00	8155.9	32.6	100	48
2.00	8247.2	32.7	100	48
3.00	8169.5	32.7	100	48
4.00	8438.7	32.4	100	48
5.00	7935.2	30.7	8726	14224
6.00	7543.1	31.0	10905	8432
7.00	8091.9	30.3	9823	4544
8.00	8119.6	30.2	4557	48
9.00	8132.8	30.2	6482	48
10.00	8141.9	30.2	4183	48
11.00	8143.8	30.2	100	48
12.00 AM	8151.8	30.3	100	48

Table 6. Inflows and Outflows to Lake Keowee, August 25, 1978

TIME Aug. 25 1978	OCONEE DISCHARGE (m^3/min)	OCONEE DISCHARGE TEMP. °C	NET JOCASSEE FLOW (CFS)	KEOWEE HYDRO FLOW (CFS)
12.00 AM	8151.8	30.3	100	48
1.00	7952.3	28.9	4938	3576
2.00	7097.2	28.5	838	608
3.00	7098.4	29.1	100	48
4.00	7098.8	29.6	100	48
5.00	7103.7	30.0	100	48
6.00	7102.6	30.5	100	48
7.00	7104.4	30.7	100	48
8.00	7279.7	30.9	100	3484
9.00	8012.8	30.5	100	8624
10.00	7760.4	30.7	100	9352
11.00	7759.2	30.9	100	1392
12.00 PM	8059.8	30.7	1632	2564
1.00	8130.6	30.8	5442	8820
2.00	8112.8	30.9	11553	9500
3.00	8141.9	31.1	19048	7624
4.00	8102.2	31.3	17180	7856
5.00	8108.6	31.3	10615	8852
6.00	8107.5	31.4	10158	8172
7.00	8110.1	31.5	10076	2660
8.00	8114.7	31.5	2185	48
9.00	8126.8	31.5	29.83	48
10.00	8148.3	31.5	3151	48
11.00	8141.9	30.4	2647	48
12.00 AM	8141.9	30.3	100	48

Table 7. Meteorological Data for Lake Keowee, August 24, 1978

Time (Hrs. from midnight)	Wind Speed (m/s)	Air Temp (°C)	Dew Pt. Temp. (°C)	Solar Radiation (w/m^2)	Wind Direction
1	1.788	21.9	21.94	0.0	30.0
2	2.76	21.4	21.39	0.0	10
3	1.96	20.8	20.83	0.0	30.0
4	2.53	20.8	20.83	0.0	20
5	7.45	20.3	20.28	0.0	35.0
6	2.27	20.0	20.0	0.0	20.0
7	1.38	19.4	19.4	34.85	30.0
8	2.85	20.4	20.0	170.77	15.0
9	1.56	21.4	20.83	326.43	10.0
10	1.29	23.3	21.67	592.45	40.0
11	1.69	26.1	23.06	710.94	20.0
12	1.96	27.2	23.89	815.49	30.0
13	2.90	28.1	24.44	864.28	40.0
14	2.86	28.9	25.56	836.4	15.0
15	2.90	29.4	25.83	752.76	85.0
16	1.82	29.4	25.28	599.42	60.0
17	1.78	29.4	25.28	397.29	70.0
18	1.42	29.4	26.67	214.9	85.0
19	1.47	29.9	26.53	81.32	75.0
20	1.16	27.2	25.97	5.81	90.0
21	0.71	25.8	25.28	0.0	30.0
22	1.82	25.28	25.0	0.0	20.0
23	1.16	24.17	24.17	0.0	5.0
24	1.61	23.89	23.89	0.0	25.0

Table 8. Meteorological Data for Lake Keowee, August 25, 1978

Time (Hrs. from midnight)	Wind Speed (m/s)	Air Temp (°C)	Dew Pt. Temp. (°C)	Solar Radiation (w/m^2)	Wind Direction (Degrees)
1	1.028	23.1	23.0	0.0	55.0
2	2.951	23.1	23.0	0.0	40.0
3	2.414	22.2	22.2	0.0	20.0
4	2.995	22.2	22.2	0.0	55.0
5	1.833	21.9	21.9	0.0	30.0
6	1.833	21.7	21.7	0.0	35.0
7	2.235	21.4	21.4	0.0	25.0
8	1.922	21.7	21.7	27.89	40.0
9	1.833	23.3	20.0	168.52	10.0
10	0.760	25.3	17.2	348.67	15.0
11	1.162	26.9	18.3	534.62	10.0
12	1.565	28.6	16.1	691.52	45.0
13	1.654	29.7	16.9	796.12	55.0
14	1.967	30.6	16.7	1041.35	55.0
15	2.503	30.8	16.1	807.74	70.0
16	2.012	30.8	16.1	708.96	45.0
17	2.056	30.8	16.7	575.30	55.0
18	1.743	30.0	20.0	284.74	90.0
19	1.967	29.4	22.7	185.96	80.0
20	1.654	28.3	21.1	58.11	70.0
21	2.414	27.2	25.6	0.0	65.0
22	1.341	25.8	25.6	0.0	90.0
23	1.073	25.6	25.6	0.0	10.0
24	3.085	25.6	25.6	0.0	40.0

Table 9. Inflows and Outflows to Lake Keowee, February 27, 1979

TIME Feb. 27, 1978	OCONEE DISCHARGE (m^3/min)	OCONEE DISCHARGE TEMP. (°C)	NET JOCASSEE FLOW (C.F.S.)	KEOWEE HYDRO FLOW (C.F.S.)
12.00 AM	7505.3	18.6	-14395	48
1.00	7498.1	18.5	-18754	48
2.00	7492.0	18.4	-18805	48
3.00	7492.0	18.5	-18713	48
4.00	7491.6	18.3	-18698	48
5.00	7494.3	18.3	-18688	48
6.00	7488.2	18.3	-15939	48
7.00	7481.8	18.2	3484	3668
8.00	7485.6	18.3	16823	17540
9.00	7488.2	18.2	13503	8488
10.00	7497.7	18.3	5470	8096
11.00	7504.1	18.3	100	2680
12.00 PM	7503.4	18.4	100	48
1.00	7506.0	18.5	100	48
2.00	7506.4	18.5	100	48
3.00	7503.4	18.5	100	48
4.00	7501.9	18.4	100	48
5.00	7507.5	18.4	100	48
6.00	7511.0	18.4	100	48
7.00	7516.2	18.4	100	48
8.00	7518.9	18.3	100	48
9.00	7520.4	18.3	100	48
10.00	7516.6	18.2	100	48
11.00	7509.4	18.2	100	48
12.00 AM	7507.2	18.2	-4382	48

Table 10. Inflows and Outflows to Lake Keowee, February 28, 1979

TIME Feb. 28, 1978	OCONEE DISCHARGE (m^3/min)	OCONEE DISCHARGE TEMP. (°C)	NET JOCASSEE FLOW (C.F.S.)	KEOWEE HYDRO FLOW (C.F.S.)
12.00 AM	7507.2	18.2	-4382	48
1.00	7616.4	19.8	-18050	48
2.00	7655.5	19.5	-18621	48
3.00	7356.3	19.8	-18602	48
4.00	7233.4	20.1	-18692	48
5.00	7494.7	19.5	-18559	48
6.00	7605.3	19.1	-15139	48
7.00	7618.6	19.1	3045	48
8.00	7300.2	19.5	19245	5788
9.00	7239.8	19.5	8338	48
10.00	7241.9	19.4	100	48
11.00	7243.0	19.3	100	48
12.00 PM	7246.2	19.1	100	48
1.00	7239.0	19.0	100	48
2.00	7241.0	18.9	100	48
3.00	7235.3	18.9	100	48
4.00	7207.8	18.9	100	48
5.00	7196.3	18.7	100	48
6.00	7200.0	18.9	100	48
7.00	7211.5	19.2	100	48
8.00	7212.	19.0	100	48
9.00	6829.4	18.3	100	48
10.00	7189.1	18.5	100	48
11.00	7287.8	18.1	-1544	48
12.00 AM	7036.7	15.8	-15141	48

Table 11. Meteorological Data for Lake Keowee, February 27, 1979

Time (Hrs from midnight)	Wind Speed (m/s)	Air Temp (°C)	Dew Pt. Temp. (°C)	Solar Radiation (w/m^2)	Wind Direction (Degrees)
1	1.833	-0.33	-2.78	0.0	15°
2	1.073	-0.72	-1.67	0.0	75°
3	2.325	-1.61	-1.61	0.0	60°
4	1.565	-2.22	-2.28	0.0	15°
5	2.056	-1.83	-1.89	0.0	50°
6	1.788	-2.17	-2.22	0.0	85°
7	2.012	-2.72	-2.78	20.94	85°
8	2.280	-1.67	-2.78	195.39	60°
9	0.626	0.01	-3.33	369.85	5°
10	1.386	3.06	-2.22	544.31	75°
11	1.609	5.83	-2.22	655.96	15°
12	1.788	8.83	-1.39	725.75	40°
13	3.129	11.06	-2.78	746.68	80°
14	2.593	12.28	-5.0	704.81	70°
15	1.520	13.39	-5.56	579.20	80°
16	1.207	13.89	-5.56	383.81	75°
17	1.565	13.83	-5.61	146.55	55°
18	1.609	13.72	-3.33	20.94	15°
19	2.056	11.72	-4.44	0.0	30°
20	1.162	9.72	-2.78	0.0	25°
21	2.772	8.33	5.28	0.0	55°
22	2.861	7.78	5.56	0.0	55°
23	2.995	7.00	5.28	0.0	50°
24	1.386	5.28	3.89	0.0	60°

Table 12. Meteorological Data for Lake Keowee, February 28, 1979

Time (Hrs. from mid night)	Wind Speed (m/s)	Air Temp (°C)	Dew Pt. Temp. (°C)	Solar Radiation (w/m^2)	Wind Direction (Degrees)
1	2.280	4.94	4.17	0.0	55
2	2.101	4.00	4.17	0.0	55
3	1.967	3.00	2.22	0.0	60
4	2.414	2.28	1.67	0.0	50
5	2.593	2.61	2.22	0.0	80
6	4.068	4.11	3.06	0.0	75
7	3.398	3.83	0.28	20.94	60
8	3.934	4.22	-2.78	153.52	60
9	4.515	6.67	-3.89	279.13	85
10	4.381	7.78	-5.00	439.64	60
11	3.710	9.28	-5.00	676.90	70
12	2.235	10.78	-3.89	907.18	45
13	1.878	11.72	-3.89	537.33	60
14	1.609	12.28	-3.89	565.24	50
15	3.442	13.33	-3.33	690.85	45
16	2.950	13.61	-2.78	0.0	45
17	2.325	13.33	-1.67	0.0	45
18	2.012	12.72	-0.56	0.0	5
19	2.235	11.39	1.39	0.0	65
20	2.950	10.39	2.28	0.0	55
21	2.772	10.61	2.22	0.0	85
22	2.638	10.44	2.22	0.0	50
23	2.191	10.00	2.22	0.0	65
24	2.369	9.83	2.22	0.0	70

Table 13. Catalogue of Runs for 3-D Lake Keowee

Run Identification	Wind (M/Sec)	Current (Cm/Sec)	Discharge Velocity (Cm/Sec)	Discharge Temperature (^{o}C)	Depth (Meters) Variable	Depth (Meters) Constant	Remarks
L001 (Selection of B.C.'s and I.C.'s	No	No	5.65	32.3	No	Yes (16 Meters	Total Simulated Time: 21.60 Hrs.
L002 (Model Execution for One Physical Parameter - Variable Depth)	No	No	5.65	32.3	Yes	No	Total Simulated Time: 8.64 Hrs.
L003 (Model Execution for Two Physical Parameters - Depth and Wind	4.00	No	5.65	32.3	Yes	No	Total Simulated Time: 8.64 Hrs.
L004 (First Execution for Archival Data	12.83	0.69	5.65	32.4	Yes	No	Total Simulated Time: 8.64 Hrs.
L005 (Second Execution for Archival Data) Up Date: L006 (For Ground Truth Data)	12.83	0.69	5.65	32.4	No	Yes (16 Meters)	Total Simulated Time: 32.4 Hrs.
L006 August 24/25 Data Base Comparison	Variable (0.76 to 3.09)	Variable (0.61 to 1.12)	7.42	18.4	No	Yes (16 Meters)	Total Simulated Time: 48 Hours
L007 February 27/28 Data Base Comparison	Variable (1.61 to 4.52)	Variable (0.61 to 4.14)	6.84	18.4	No	Yes (16 Meters)	Total Simulated Time: 48 Hours

Table 14. Root Mean Square Difference Between IR and Predicted Temperatures

Time	RMS Difference
Morning, August 24, 1978	0.55 °C
Morning, August 25, 1978	0.34 °C
Afternoon, February 27, 1979	0.82 °C
Morning, February 28, 1979	0.01 °C